CHAPTERS

ON

ELECTRICITY

AN INTRODUCTORY TEXT-BOOK FOR STUDENTS IN COLLEGE

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WITH A COURSE IN ELECTRICAL MEASUREMENTS.

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SHELDON'S CHAPTERS ON ELECTRICITY

SECOND EDITION

PREFACE.

THESE Chapters on Electricity, prepared for and included in the Fourth Revised Edition of Olmsted's College Philosophy, are here offered in a separate volume. They are intended for use as a text-book by students in those colleges which devote but thirty or forty hours to the subject. The principles presented are those which ought to be known by every liberally educated person. The economy of space necessitated by a clear and thorough presentation within such limits, has required the omission of detailed descriptions of apparatus and of demonstrative experiments. To master these chapters will require more effort on the part of a student than to master an equal number of pages in a more extended treatise. For the same efforts, however, he will obtain a knowledge of a greater number of principles. Furthermore, he will more readily perceive the correlation between different parts of the subject. Even an ordinary comprehension of the subject signifies a knowledge of many of these mutual relations.

It has been the desire of the author to present each part of the subject in its most modern dress. This desire, however, has been tempered by a consideration of the intended functions of the book.

POLYTECHNIC INSTITUTE OF BROOKLYN,
June, 1891.

IN the present edition a few typographical errors have been corrected, and a Course in Electrical Measurements has been added. This course is written in the form of a laboratory manual in which specific directions are given to the student. The experience of the author has shown that such a manual results in a saving of time both to the instructor and the student. The enthusiasm of the student is better maintained when his results are fairly accurate and of frequent occurrence. A meagre laboratory equipment is sufficient for carrying on the course, and the accuracy of the results obtained will depend almost entirely upon the student and the instructor.

POLYTECHNIC INSTITUTE OF BROOKLYN,
July, 1895.

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PART VII.

ELECTRICITY AND MAGNETISM.

CHAPTER I.

ELECTROSTATICS.—POTENTIAL.—CAPACITY.

557. **Definition.**—The name *Electricity*, from the Greek word for *amber*, is given to a peculiar agency, which causes mutual attractions or repulsions between light bodies, and which, under proper conditions, also produces heat, light, sound, and chemical decomposition.

Lightning and thunder are familiar illustrations of the intense action of this agency.

558. **Common Indications of Electricity.**—If amber, sealing-wax, or any other resinous substance, be rubbed with dry woollen cloth, fur, or silk, and then brought near the face, the excited electricity disturbs the downy hairs upon the skin, and thus causes a sensation like that produced by a cobweb. When vulcanite is strongly excited, it gives off a spark to the finger held toward it, accompanied by a sharp snapping noise. A sheet of writing-paper, first dried by the fire, and then laid on a table and rubbed with India-rubber, becomes so much excited as to adhere to the wall of the room or any other surface to which it is applied. As the paper is pulled up slowly from the table by one edge, a number of small sparks may be seen and heard on the under side of the paper. In dry weather, the brushing of a garment causes the floating dust to fly back and cling to it.

Bodies are said to be electrically *excited* when they show signs of electricity in consequence of some mechanical action performed upon them, as in the experiments already described.

A body is *electrified* when it receives electricity, by communication, from another body already *excited* or *electrified*.

559. **Repulsion.**—An electrically excited body does not always produce attraction. It will be noticed that pith-balls, after

coming in contact with an electrified body, which has attracted them, are repelled. They have received a portion of the electricity which attracted them and repulsion is the result. This repulsion can be made much more apparent if an electrified vulcanite rod be suspended in a wire loop at the end of a silk thread and then a similarly electrified rod be approached to it. The suspended rod can be made to revolve rapidly because of the repulsion.

560. Theories of Electricity.—As to the exact nature of electricity science is still in the dark, though probably the darkness which precedes dawn.

Symmer proposed a *"two-fluid" theory.* He supposed every unelectrified body to contain equal quantities of two opposite kinds of imponderable electric fluid. In equal quantities they neutralized each other. But if, by friction or other means, the amount of one fluid be made to exceed that of the other, then the body becomes positively or negatively electrified. According to this theory two positively or two negatively electrified bodies repel each other; a positively electrified body and a negatively electrified body attract each other.

Franklin modified this into a *"one-fluid" theory.* Every body contains its own normal amount of one electric fluid. This amount is increased or decreased when rubbed by another body. The surplus amount is obtained from or given up to this second body. The body with more than its normal amount is positively electrified, and negatively electrified when it has less than this amount.

Lodge maintains that electricity is the luminiferous ether itself. He arrives at this conclusion after considering a great number of electrical phenomena which demand the ether for their proper explanation.

Without adopting any theory, electrical laws and phenomena may be understood by considering the fact that a body may be subject to two opposite electrical conditions. It may be positively or negatively electrified. The law regarding attraction and repulsion then is:

Similarly electrified bodies repel each other, and dissimilarly electrified bodies attract each other.

561. Electric Series.—If two bodies are rubbed together, one of them is electrified positively and the other negatively. One of these bodies, if rubbed by a third, may be oppositely electrified to what it was in the first case. Silk, when rubbed with glass, is negatively electrified; but rubbed with sulphur, it receives a positive charge. In the following series each member becomes

positively charged when rubbed on one following it, negatively when rubbed on one preceding it: *fur, wool, resin, glass, cotton, silk, wood, metals, sulphur, india-rubber, gutta-percha.*

562. **Conductors and Insulators.**—When a glass or vulcanite tube is rubbed with cat's fur, it shows that it has become electrified by attracting light articles. If a metal rod be substituted for the glass one, no attraction will be evidenced. This is not because the metal was not electrified by the rubbing, but because the electricity, as soon as generated, escaped, through the rod itself and the hand holding it, to the ground. If the rod be held by a glass or hard-rubber handle and then rubbed, it will attract as the glass did. This shows that some substances, as metals, allow electricity to pass freely through them, while others, as glass, almost entirely prevent its passage. The first class of substances are called *conductors*, the latter class *non-conductors* or *insulators*. Some substances neither conduct nor insulate well, but lie between the two classes. The following is a table of substances arranged in the order of their electrical conductivity:

CONDUCTORS.	4. Acids.	8. Wood.	12. Glass.
1. Metals.	5. Sea-water.	9. Silk.	13. Shellac.
2. Charcoal.	6. Vegetables.	10. India-rubber.	14. Vulcanite.
3. Graphite.	7. Animals.	11. Porcelain.	INSULATORS.

A conductor mounted upon or suspended by an insulator is said to be insulated.

A method for determining the conductivity of substances is to suspend two pith-balls by moistened threads from a metal insulated hook. Upon communicating a charge of electricity to the balls they will stand out away from each other, owing to the repulsion between the same kinds of electricity on each. If, now, one end of the substance, whose conductivity is to be determined, be held in the hand and the other be touched to the hook from which the balls are suspended, the rapidity with which the balls fall toward each other determines the conductivity. If they fall instantly, the substance is a good conductor. If they remain separated, the substance is a good insulator. After an insulator or an insulated conductor has been charged with electricity, the electricity of necessity remains at rest, and is, for this reason, called *statical electricity*. If, now, it be connected, by means of a conducting wire, with the moist earth, it will pass off instantly to the earth. During the time of its passage it is called *dynamical electricity*. If by chemical or other means the flow be maintained, then the dynamical electricity is called *galvanic* or *voltaic*.

563. **Coulomb's Law.**—Coulomb showed that, correspond-

ing to Newton's law of gravitation, *the force of attraction between dissimilarly electrified bodies and the force of repulsion between similarly electrified bodies is directly proportional to the product of the quantities of electricity and inversely proportional to the square of the distance between the bodies.*

If we represent the force by f dynes, the distance by r centimetres, and the quantities of electricity by q and q', then we can indicate the law by the equation

$$f = \frac{q\,q'}{r^2}.$$

If these magnitudes be connected by the sign of equality, a proper unit of quantity must be had. Letting $f = 1$ dyne, $r = 1$ centimeter, and $q = q'$, then $q^2 = 1$ and $q = \pm 1$. Hence we may define the unit of electrical quantity as follows:

One unit of electricity is that quantity which, when placed at a distance of one centimetre from a similar and equal quantity, repels it with a force of one dyne.

If the quantity of electricity be spread over a body of some size, as a sphere, then the distance r must be measured from some point as the centre of the sphere. This is evidently for the same reason as in gravitation, where the distance is measured from the centre of gravity.

It must be borne in mind that the unit of quantity here given is based upon the force exerted by two *statical* quantities of electricity. Another unit, based upon the *electro-magnetic* force, will be mentioned later.

564. Potential.—Whenever a body is lifted vertically away from the earth, the work performed in lifting it has been transformed into potential energy. The body has, because of the attraction between it and the earth, a potential energy capable of doing exactly the same number of ergs or foot-pounds of work as were used in raising it to its position (Art. 36). Similarly, if two conductors, charged with the same kind of electricity, be approached towards each other, a certain number of ergs of work will have been performed, owing to the repulsion between them. (A more perfect analogy would be to suppose two dissimilarly charged conductors to be separated.) The work which has been performed is also changed into potential energy between the conductors. The amount of energy made potential depends upon the quantities of electricity on each of the conductors, and upon the distance through which they have been moved toward each other. For energy is measured by the work it can do, and work in ergs equals the product of the force in dynes by the distance in centi-

metres through which it has acted. Now the force of repulsion between the two conductors equals the product of their quantities divided by the square of their distance apart.

Suppose one of the conductors to have any charge and to be fixed immovably. Then let three charges of respectively 1, 2, and 3 units of quantity be successively approached, between the same limits, towards the first conductor. In the first case a certain amount of energy will have been made potential; in the second case twice as much, and in the third three times as much. Evidently a certain amount of the energy made potential is owing to the immovable charge, and this amount is the same in each case. The condition of the space around an electrified body is termed the *potential,* owing to that charge. To obtain a quantitative expression for it, the movable charge must be taken of unit quantity. It must also be considered that the work necessary to approach an unit through a given distance is not as great as to approach it through twice that distance. Considering these two points, we have the definition of electrostatic potential:

The potential at any point is the work that must be spent upon a unit of positive electricity in bringing it up to that point from an infinite distance.

If the immovable charge be negative, no work would be required to move up a positive unit; on the contrary, work would be performed by the unit in travelling. Hence the potential, owing to a negative charge, is *negative potential.* It is convenient to consider it so.

565. Equipotential Surfaces.—If the charge of electricity be supposed to lie on a small sphere, then some point can be found on every possible radius of the sphere produced where the potential will be the same. That is, it would require the same amount of work to bring a positive unit of electricity from an infinite distance out on each radius to this point. In the case of a sphere being charged, these points would be equally distanced from the centre of the sphere. If now these points be connected together, a spherical surface will result. Any such surface which contains only points of the same potential is called an *equipotential surface.*

In order that an equipotential surface may be spherical, the charge must lie upon a sphere and must be free from other electrified bodies. If the electrified body be irregular in shape, the equipotential surfaces will be correspondingly so.

To transfer a quantity of electricity from one point in an equipotential surface to another in the same surface requires no work to

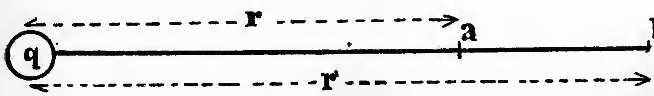
be performed. For while it may require work to move the charge in one direction from the surface, it will require a negative expenditure of work to bring it back again, *i.e.*, the attraction or repulsion between the electricities performs the work.

566. Difference of Potential.—In the consideration of most problems in electricity involving the idea of potential, the potential of two points is required. However, it is not the absolute potential of each of the points, but the difference of potential between them which is considered. If it requires a certain number of ergs to bring a unit of positive electricity from an infinite distance up to a given point, and more ergs to bring it up to a second point, then this extra work is what would be required to move the unit from the first to the second point. This number of ergs is then the measure of the difference of potential between the two points. Hence we obtain the definition:

The unit difference of potential is that which must exist between two points, that one erg may be required to move a positive unit of electricity from one to the other.

567. Unit of Potential.—The difference of potential between two points, a and b, Fig. 315, at distances r and r' from a quantity

FIG. 315.



of electricity q, is measured by the work necessary to move a positive unit of electricity from b to a.

This

work = (*average*) *force* × *distance through which it is overcome.*

The distance $= r' - r$.

$$\left.\begin{array}{l}\text{Force at } a = \dfrac{q}{r^2}\\[2ex] \text{Force at } b = \dfrac{q}{r'^2}\end{array}\right\}\ \text{average force} = \sqrt{\frac{q^2}{r^2\ r'^2}} = \frac{q}{r\ r'}*$$

Hence the difference of potential

$$V_a - V_b = \frac{q}{r\ r'}(r' - r) = q\left(\frac{1}{r} - \frac{1}{r'}\right).$$

This equation for the difference of potential between two points enables us to obtain an equation for the absolute potential V_a at

* That this is a true average can be proved by a simple application of the calculus.

any point a. We have only to suppose that the second point b is removed to an infinite distance, where its potential $V_b = 0$, and $r' = \infty$. Hence

$$V_a = \frac{q}{r},$$

Or, in general,

The potential, V, of any point at a distance, r, from a quantity of electricity, q, is expressed by the equation,

$$V = \frac{q}{r}.$$

From this equation, supposing q and r each equal to unity, we obtain the definition:

The unit potential is that due to a unit quantity of electricity at a distance of one centimetre.

The potential at a point owing to several charges of electricity is equal to the sum of the potentials at that point due to each charge taken separately. Thus, if quantities of electricity q, q', and q'' are at distances r, r', and r'' from a point, the potential at that point

$$V = \frac{q}{r} + \frac{q'}{r'} + \frac{q''}{r''}.$$

568. Zero Potential.—At an infinite distance away from any electrified body the potential would evidently be zero. If a positive charge were brought near, the potential would become positive, and negative for a negative charge. In practice it is convenient to take the earth as a standard zero, with which all other potentials may be compared. This assumption is analogous to the use of the sea-level as the zero in measuring the heights of mountains instead of the centre of the earth.

569. Potential on a Sphere.—By discussing the equations in Art. 567, and supposing r equal to zero, one might be led to think that the potential would be infinite. But it must be remembered that, just as in gravitation, there is a centre from which all electric force apparently works. In the case of the earth all attraction is toward the centre of gravity. With an electrified sphere all action comes from the centre of the sphere. The electricity (Art. 572) lies upon the surface of it, but the resultant of all attractions from all the particles of electricity passes through the centre. Thus a point in the electricity itself on a charged conductor has a finite potential, and, *in the case of a sphere, it is equal to the quantity of electricity divided by the radius of the sphere.*

570. Capacity.—Suppose that a point on the surface of a charged spherical conductor, *i.e.*, any point in the electricity itself,

to have a certain potential. If, now, the radius of the sphere be supposed to grow smaller, while the quantity of electricity remains the same, then the potential will evidently increase as the radius decreases, because the potential $V = \frac{Q}{r}$. Thus a large sphere, *e.g.*, the earth, can hold a large quantity of electricity without having a high potential. This ratio between quantity and potential of electricity in a conductor is termed the *electrostatic capacity* of the conductor. Representing this by C, we have the definition in the form of an equation:

$$C = \frac{Q}{V}.$$

From this, by supposing Q and V each equal to unity, we have the definition,

That conductor has a unit of electrostatic capacity, which requires a unit quantity of electricity to raise its potential from zero to one.

Applying the above equation to a sphere of radius r we have

$$V = \frac{Q}{C} = \frac{Q}{r},$$

whence we see that the electrostatic capacities of spheres are equal to their radii. Accordingly a sphere of 1 centimetre radius has a unit capacity.

A conductor, no matter what its shape, will have a capacity, and we may say that,

The capacity of any conductor is equal to the number of units of quantity of electricity necessary to raise its potential from zero to unity.

571. Equipotential of Connected Conductors.—When a conductor is charged with electricity each particle strives to get out of the reach of its neighbors, because of the natural repulsion between like kinds of electricity. The particle, however, cannot escape, because the dry air is an insulator. If, now, it be connected, by means of a conducting wire, with the earth, the particle, followed by others, will flow off to the earth. Now the earth, having such a very large radius, would require an enormous quantity of electricity to raise its potential even an infinitesimal amount. The result is that the potential of the conductor and earth are both reduced to zero. Suppose, however, that instead of being connected with the earth it had been connected to another insulated conductor. The particles escaping from the first conductor would gradually raise the potential of the second until a particle, at some place on the connecting wire, would be equally repelled by the charges on each conductor, and would accordingly

remain at rest. Now it will be found that, just as when two vessels, one of which contains water, when connected by a tube at the bottom, will allow the flow of water until the level in both is the same, so with these conductors, the potentials of both will have become the same because of the connecting wire. Furthermore, just as is the case with the connected vessels of water, it makes no difference whether the second conductor had originally a charge of electricity or not. The potential of all electrostatically charged conductors becomes the same when connected together.

If the potential of connected conductors becomes the same, then it is quite evident the total quantity of electricity must be so divided that each conductor shall have a quantity in direct proportion to its capacity. This must necessarily follow from the definition of capacity at the end of Art. 570. Thus three connected conductors of capacities 1, 2, and 3 would have respectively one-, two-, and three-sixths of the total quantity of electricity upon them.

572. Position of Static Charge.—A statical charge of electricity always resides on the outside surface of a conductor. It also resides on the outside of the geometrical figure of the conductor. Thus, if a charge be communicated to a wire bird-cage, it will reside wholly on the outside half of the wires and none will lie on the inside. This may be shown in many ways.

If a hollow, insulated, conducting cylinder (Fig. 316) be provided with two suspended pith balls in the interior and two on the exterior, and a charge of electricity be communicated to it, the outside balls will diverge, owing to the repulsion of like electricities. The inside balls will, on the other hand, remain at rest. It makes no difference whether the charge be communicated to the inside or outside. As soon as it has been communicated the inside balls drop to their normal position.

FIG. 316.

In calculating the capacities of conductors, it makes no difference whether a conductor is solid or hollow.

573. Distribution of a Charge on the Surface.—Statical electricity resides at the surface of a body, as we have seen, but is not uniformly diffused over it, except in the case of the sphere. In general, the more *prominent* the part, and the more *rapid its curvature*, the more intensely is the electricity accumulated there.

In a long, slender rod the density is greatest at the ends, nearly the whole charge being collected at these points. On a sphere,

not influenced by other electrified bodies, the density is uniform, as illustrated in Fig. 317, the dotted line denoting by its constant distance from the surface the uniform distribution of the charge.

Fig. 318 represents the varying density upon an ellipsoid.

FIG. 317.

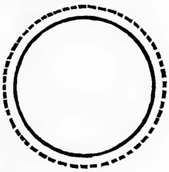


FIG. 318.

The two ellipsoids are similar, and the ellipsoidal shell included between them represents the densities at various points. In this case the densities at any two points of the ellipsoid are nearly proportional to the diameters through those points.

The student must remember that the charge does not form a layer upon the body in any sense whatever, and that the above figures are given merely to aid the memory in retaining the law of distribution.

574. Surface Density.—The greater the quantity of electricity on a given conductor, the greater the tendency is for the electricity to escape to surrounding objects.

The surface density at any point of a surface, when the distribution is uniform, is the quantity of electricity per square centimetre of surface.

If Q units of electricity reside on S square centimetres of surface, then the surface density d is represented by the formula

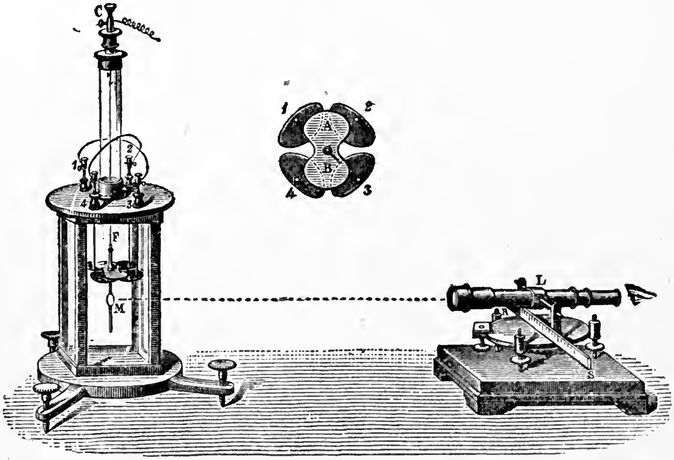
$$d = \frac{Q}{S}.$$

The surface of a fine point is very small, hence, if there is any quantity of electricity supplied to it, the density becomes very great and the charge escapes into the air.

575. Quadrant Electrometer.—This instrument is used for determining very accurately differences of electrical potential. A simple form, suited for qualitative work, is shown in Fig. 319. Four like pieces of metal are suspended, by conducting rods, from the insulating top of a glass case. They are symmetrically placed (as shown in the small figure) and are fixed in position. Over these quadrants, as they are termed, swings a flat aluminum needle, suspended by a wire of small diameter. This prolonged suspension hangs in a glass chimney, placed upon the top of the

case. A small mirror, *M*, is attached to a rigid prolongation of the suspension, prolonged beneath the needle. This mirror

FIG. 319.



serves to reflect the image of a scale, *S*, through a reading telescope, *L*, by means of which deflections of the needle can be observed.

To use the instrument, the needle is charged, through its suspending wire, to a constant potential. This may be done by connecting *C* with the knob of a charged Leyden jar. The diagonally opposite quadrants are connected together, and the two pairs connected with the points whose difference of potential is to be determined. Now suppose that 2 and 4 (small diagram) were of higher potential than 1 and 3. They would exert a greater force upon the needle than 1 and 3, and according to the sign of the charge on the needle, would cause rotation of the needle in one direction or another. The needle, which was held in the zero position by the torsion of its suspension, would come to rest at a place where the force of torsion was equal and opposed to the electrical force. For small deflections the forces are proportional to the tangents of the angle, *i.e.*, to the readings of the scale.

For very accurate work many complicated attachments are added to this simple form.

Problems.

1. Two conductors, of capacity 10 and 15 respectively, are connected by a fine wire and a charge of 1000 units is divided between them: find the charge which each takes, and the potential to which each is raised.

2. Three spheres of radii 1, 2, and 3 cm. are charged to potentials 3, 2, and 1 respectively, and are then connected by a fine wire: what is their common potential?

3. Two spheres, of capacity 2 and 3, are charged respectively to potentials 5 and 10: what will be their common potential, if they are placed in electrical connection?

4. Two spheres, of 2 and 6 cm. radius, are charged respectively with 80 and 30 units of electricity; compare their potentials. If they are connected by a fine wire, how much electricity will pass along it?

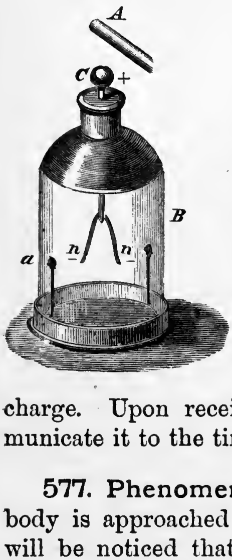
5. Twelve units of electricity raises the potential of a conductor from 0 to 3: what is its capacity?

CHAPTER II.

ELECTROSTATIC INDUCTION.

576. Gold-leaf Electroscope.—The gold-leaf electroscope is a delicate instrument for detecting the presence of electricity. It consists (Fig. 320) of a folded strip of gold-leaf, suspended from the end of a brass rod, which penetrates the stopper of a glass insulating receiver. The outside end of the rod is provided with a brass ball. Whenever a charge of electricity is communicated to the ball the gold-leaves partake of it and diverge from each other, because of the repulsion of like kinds of electricity. The sides of the receiver are provided with strips of tin-foil, which are in electrical communication with the earth through the base. The object of these is to prevent the rupturing of the gold-leaves by the sudden communication of too great a charge. Upon receiving such a charge they diverge and communicate it to the tin-foil and it escapes thence to the earth.

FIG. 320.



577. Phenomena of Induction.—Whenever an electrified body is approached toward the brass ball of an electroscope, it will be noticed that, while it is even a great distance away from it, the gold-leaves begin to separate and show the presence of electricity upon them. This electricity is the result of the presence

of an electrified body in the neighborhood and is called *induced* electricity. The process under which it was generated is termed *electrostatic induction.*

Whenever a charged conductor is brought near to an uncharged conductor, and is separated from it only by an insulator, which in this case is called a *dielectric*, the uncharged conductor undergoes an electrical change. The side which is toward the first conductor is charged with an opposite kind of electricity, while the remote side has a charge of same kind as the original charge.

Thus (Fig. 320), if a negatively electrified piece of hard rubber be brought near to the gold-leaf electroscope and is separated from it by air for a dielectric, there will be positive electricity induced on the nearer side of the electroscope, which is the ball, and negative on the remote, which includes the gold-leaves. The leaves accordingly diverge. The electricity on A is called the *inducing* charge, that in the electroscope the *induced charge.*

Whenever an insulated conductor, which contains the two kinds of induced electricity and is still under the influence of the inducing charge, is connected with the earth, the electricity of the same kind as the inducing charge will escape to the earth. This is because of the repulsion between like kinds of electricity. It is equally true whether the near or remote side of the conductor is connected to the earth.

The remaining opposite kind, however, cannot escape because of the attraction exerted by the original inducing charge. If now the earth connection be removed, it will be found that only a small portion of the original inducing charge can escape when connected to the earth. It is held in place by an opposite kind of electricity, which it has itself produced. These two opposite electricities, separated by a dielectric, are said to be *bound*, while electricity free to follow an earth connection is called *free* electricity.

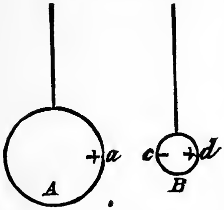
For illustration, suppose that the apparatus is in the condition represented in Fig. 320. If the finger be touched at C, the electricity $n\ n$ will escape to the earth and the leaves will collapse. The positive charge at C remains bound by A's charge. If now A be removed, this charge will diffuse over the electroscope and the leaves will diverge because of the portions which they receive.

As might be expected, successive inductions may be obtained from one original charge. The induced charge in one case acts as the inducing charge in a new induction.

578. Induction Precedes Attraction.—Whenever a body is attracted because of the charge of electricity on another body, it is always subjected to induction before it is attracted.

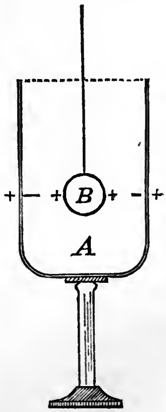
Thus, if *B* (Fig. 321) is attracted by a positive charge on *A*, the attraction is always preceded by an induction, whereby *B* is charged negatively at *c* and positively at *d*; *c* is nearer than *d*, hence the attraction between *a* and *c* is greater than the repulsion between *a* and *d*. Accordingly attraction predominates.

FIG. 321.



579. Quantity of the Induced Electricity.—The *total* quantity of electricity, of the opposite kind to its own, which a charged body induces on neighboring bodies is exactly equal to its own charge. This was experimentally proved by Faraday by means of an "ice-pail." A metallic pail, *A* (Fig. 322), was mounted upon an insulating support. The outside of the pail was connected with a delicate electroscope. Into this pail was lowered a positively charged ball, *B*, which was suspended from an insulating silk thread. Upon introducing the ball the leaves of the electroscope commenced to diverge, because the charge on *B* induced negative electricity on the interior of the pail and held it bound. The positive electricity of the pail, being free and repelled, passed partly into the electroscope. As the ball was lowered further the leaves diverged more and more until, after a certain depth had been reached, a further descent produced no extra divergence. Even when the ball was brought into contact with the bottom of the pail the leaves remained undisturbed and extended. Upon removing the ball, after contact, the charge was found to have disappeared from it. The fact that the gold-leaves were undisturbed by the contact of the ball with the pail proves that there was the same quantity of negative electricity on the inside of the pail as positive electricity on the ball. Coming together the two neutralized each other and left the positive outside charge undisturbed.

FIG. 322.



580. Condensers.—If a pane of glass be taken, and a piece of tin-foil be pasted upon the middle of each face of the pane, and one piece be charged positively, the inner surface of the other piece will receive a negative charge by induction. If the second piece be connected with the earth positive electricity will escape. The positive electricity of the first tin-foil will attract and hold the negative of the second *bound*. If the connections to the source

and the earth be now removed, it will be found that hardly any electricity can be obtained by merely touching either of the foils. It may be said that each charge is inducing the other. It will be found that these two pieces of tin-foil may be, when thus arranged, much more strongly charged than either of them could possibly be, if it were placed alone upon a piece of glass and then electrified. In other words, the capacity of a conductor is greatly increased when it is placed near to a conductor electrified with the opposite kind of charge. Considering then (Art. 570) that the potential $V = \frac{Q}{C}$, it will be seen that such a piece of apparatus can receive a large quantity of electricity, Q, without raising its potential, V, as much as if it were separated from all conducting or electrified bodies. Such an arrangement is called a *condenser*.

Condensers are much used in practical electricity for measuring quantities of electricity. A pane of glass, however, would not have a sufficiently large capacity for technical purposes. Accordingly commercial condensers are made by piling together alternate sheets of tin-foil and paraffined paper. The alternate layers of tin-foil are connected together. In this manner a large surface of tin-foil can be used and yet not occupy an inordinate amount of space. The capacity of a condenser varies inversely as the thickness of the *dielectric* between the conducting sheets, and directly as the product of the area of the sheets and a constant depending upon the nature of the dielectric. This constant is called the *specific inductive capacity*.

581. Specific Inductive Capacity.—It has been stated (Art. 563) that a body charged with Q units of electricity will attract an unlike unit of electricity on a body which is r centimetres away with a force

$$F = \frac{Q}{r^2}.$$

This is strictly true only when the two bodies are in a vacuum. It is very nearly true when they are separated from each other by dry air or any other gas. That the expression for the force may be universally true, whatever be the dielectric which intervenes between the bodies, it must be modified into the form

$$F = \frac{Q}{K\,r^2}.$$

Here K is a constant, which is peculiar to each substance, and it is called the *specific inductive capacity* or the *dielectric constant* of the substance.

The following is a table of specific inductive capacities referred to air at 0° C. and 760 mm. pressure as unity:

Air and most gases	1.0
Bisulphide of Carbon	2.2
Ebonite and Rubber	2.3
Paraffin	2.3
Shellac	2.9
Sulphur	3.7
Glass	3.2 to 6.0
Water	6.0
Metals	∞

The name "inductive capacity" was introduced by Faraday in the publication of a series of experiments upon condensers. He constructed a number of exactly similar condensers, differing from each other only in the dielectric between the conducting surfaces. The dielectrics which he used were air, sulphur, shellac, and glass. He measured the capacities of these equally dimensioned condensers and found that all the others had greater capacities than the one containing air. Remembering that induction is the principle upon which the condenser works, it can readily be seen why Faraday adopted the term.

Modern writers, however, in employing the term "dielectric constant" indicate their appreciation of the important light thrown, by the mere existence of different values of K, upon the true nature of electricity. The fact that the nature of the substance between two charges of electricity influences the magnitude of their repulsions, disproves the idea that electrical attractions and repulsions are *action at a distance.* There must be something between the bodies which plays a part. Again, the repulsion of two charges of electricity, even when suspended in a vacuum, indicates that this something must be the ether. The ether, then, in different dielectrics, must in some manner be modified from what it is in a vacuum. This is known to be the case from the different optical properties of bodies.

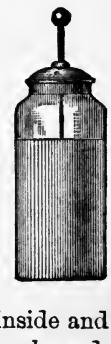
A method for showing directly the effect of K in Coulomb's law has been constructed by Mayer. Suspend horizontally a silvered circular disc of mica, 16 cms. in diameter, by a long, slender, spiral spring. Let the spring be in contact with the silvered surface. Under this disc place another of metal, which is movable in a vertical direction, and is connected to the earth. Charge the silvered mica with electricity, using the spring as a means of connection. If the distance between the two discs is but two or three centimetres, the mica will be attracted so as to extend the spring. If, now, a sheet of paraffin or plate of glass be interposed between the two discs, the attractive force will be observed to

decrease. This is because K in the denominator of the fraction expressing the force of attraction is greater for glass and paraffin than for air.

It will be noticed, in the table given, that K for metals and conductors is ∞. According to this, a charged body cannot attract a pith-ball through a metal plate. The metal is therefore called an electric *screen*. The screen must be sufficiently large to prevent any attractive force from working around its edges, and it should be connected with the earth to avoid any induced electricity from exerting an influence. It is in consideration of these facts that electrometers are surrounded by conducting cages, which are connected with the earth. Any neighboring accidental charges of electricity cannot then influence the electrometer needle.

582. **Leyden Jar.**—A most convenient form of condenser, for demonstrative experiments, is the Leyden jar. It usually consists (Fig. 323) of a glass jar coated up to a certain height on the inside and outside with tin-foil. A brass knob fixed on the end of a stout brass wire passes downward through an insulating lid and is connected by a chain with the interior coating of tin-foil. To charge the jar, it is held, by the outer coating, in the hand, and the brass knob is approached to any source of electricity. If the source furnishes positive then the internal coating becomes charged positively, and this induces and binds an equal amount of negative electricity on the outer coating, while an equal amount of positive will be rendered free and will escape through the hand to the ground. The jar being now removed, is said to be charged—there exists a state of positive potential on the inside and negative potential on the outside. Both electricities are bound, and neither can produce effects independently. If, however, they be allowed to come in connection with each other (by joining the outside coating and the ball at the top with a wire) the electricities rush to neutralize each other, and will even spark across an air gap. The jar is then said to be *discharged*. The length of the air gap through which the spark will pass depends upon the difference of potential between the inner and outer coatings. Sometimes the difference of potential becomes so great, owing to carelessness in charging, that the electricities, in striving to get together, will pierce and fracture the glass itself.

FIG. 323.



583. **Seat of the Charge.**—If a jar is made with a wide, open top, and the coatings movable, then, after charging the jar, the coatings may be removed and tested without showing any trace of

electricity upon them. If they be then replaced, the jar will be found to be charged as before removal. Benjamin Franklin inferred from this that the electricity resides upon the dielectric and the coatings serve only to readily diffuse the charge over the surface.

584. Residual Charge.—If a jar be charged, left for a time, discharged, and left for a while longer, it will be found that, upon connecting the two coatings, a spark may be obtained. The electricity remaining in the jar after the first discharge is called the *residual charge*. The amount of residual charge varies with the time that the jar has been left charged. It also depends upon the kind of dielectric used. No residual charge has been found in connection with an air-condenser.

585. Modern Theory of Condensers.—The modern ether theory of electricity gives a very satisfactory explanation of condensers. According to this theory electricity is the ether itself. When a conductor is statically charged, it is not the ether of the conductor which constitutes the charge, but the ether of the dielectric which surrounds the conductor. More exactly, charging a conductor is straining the ether particles of the surrounding dielectric out of a definite position, which they are presumed to have a tendency to remain in. Thus, if a positive charge is communicated to the inner coating of a Leyden jar, the ether particles of the glass will all be strained away from the inside. All the particles will be strained away from the inner coating and toward the outer coating. We may thus say that the inner is positively electrified and the outer negatively. We have but one ether electrification, but two ways of looking at it—just as a dent in a tin plate may be convex on one side and concave on the other.

In all dielectrics the ether particles are supposed to be held in position by elastic ties of some sort. A mechanical analogy is to represent the particle (Fig. 324) by a bead fastened to the centre of an elastic wire, clamped at both sides. When subjected to an electrifying influence, the bead is pulled to one side. Upon releasing the bead, or discharging the electricity, two things are to be noticed. First, the bead will not only go back to its original position, but will go beyond it and oscillate a number of times before coming to rest. According to this, then, the spark, at discharging a Leyden jar, should be oscillatory and made up of a succession of small sparks. Such is the case, as has been shown by reflection upon a screen from a rapidly rotating mirror. Were the spark a continuous one, its reflected

Fig. 324.

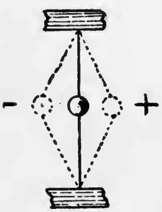


image would appear as a prolonged line. It appears, however, as a dotted line. Secondly, it must be considered that, if the strain on the wire be maintained for any length of time, it will not, upon release, immediately return to its normal position, but will assume a new one, which is displaced in the direction of the strain from the original position. This is a common phenomenon and is known as *elastic fatigue.* The electrical parallel is the residual charge. After the first discharge the ether particles have not returned to their normal position. It requires one or more residual discharges before they return to that position.

Of course in a dielectric we cannot suppose that each of the infinite number of particles of ether is supported upon anything similar to an elastic wire, for the dielectric would act well in one direction and not at all in the direction of the length of the wire. This is not in accordance with facts. Accordingly it is supposed that the dielectric acts as a mass of jelly, in which its ether particles are suspended, or possibly the ether is a jelly-like mass in itself, lacking, however, the physical property impenetrability. The jelly then exerts a restraining force to strains exerted in *any* direction upon the particles.

Conductors, on the other hand, are supposed to exercise little or no restraint upon the free movement of the ether within them.

Viewed in this light, when a positive charge is communicated to a conductor, an attempt is made to force more ether into the conductor than it ordinarily has. But the ether is absolutely incompressible. Hence room is made for the extra amount, by pressing the ether of the dielectric away from the conductor. The extra ether must have been taken from somewhere, and the place which it formerly occupied must be filled. This is done by the distention of the remote portions of the dielectric. It presses out of some conductor an equal amount of ether. We can thus see the truth of Faraday's statement that it is impossible to charge one body alone. Whenever a body is charged positively, some other body or bodies must receive an equal negative charge.

When a Leyden jar is discharged, by connecting the two coatings through a conductor, the ether in the positive coating flows toward the negative and the strain on the dielectric is relieved. This flow will, of course, be vibratory, owing to the inertia of the dielectric jelly.

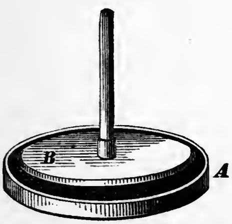
586. Hertz's Experiments.—Professor Hertz has shown experimentally that the electrical ether is wonderfully like, if not identical with, the ether presupposed in light. By rapidly charging and discharging a conductor he causes the ether upon it to surge

to and fro. This agitates the surrounding dielectric ether, and the disturbances travel in waves. The velocity of propagation he determines to be the same as the velocity of light. He has made these waves interfere, has reflected them from metal mirrors, refracted them through lenses and prisms of pitch, and has produced diffraction effects. He has shown that many optical experiments can be electrically performed by substituting dielectrics for transparent and conductors for opaque bodies.

587. Electrical Machines.—The method of rubbing sealing-wax with fur is too slow for the production of large quantities of electricity. Franklin improved upon this method, employing a machine, which rotated a large glass cylinder, the cylinder being rubbed by a silk rubber. But, at present, machines which generate electricity by friction are little used, recourse being made instead to the principle of induction. Two machines of this sort, most commonly found, are the electrophorus and the Holtz machine.

588. Electrophorus.—The electrophorus consists of a circular cake of resin, sulphur, or vulcanized rubber in a metallic base, *A* (Fig. 325), and a metallic disc, *B*, having an insulating handle. Stroking with flannel or fur electrifies the resin negatively. This induces and binds positive electricity on the lower face of the disc, when placed upon it. Free negative is repelled to the upper face. If the finger be touched to the disc, while it yet remains upon the resin, the free negative will escape to the earth. Upon then lifting the disc it will be found charged with positive electricity. This operation may be repeated indefinitely.

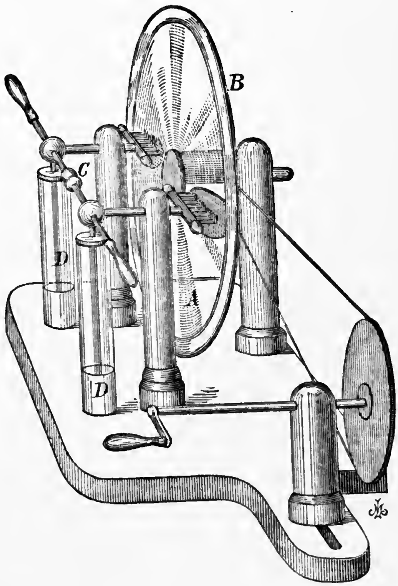
Fig. 325.



589. Holtz Machine.—This machine, illustrated in Fig. 326, consists of a revolving glass disc, *A*, and a stationary glass disc, *B*, both well coated with shellac to further insulation. In front of *A*, and close to it, as shown in the figure, are two combs connected with the discharging knobs at *C*. On the back of the disc *B*, opposite to the combs, are two paper sectors, a paper tongue or point from each projecting, through an opening (window) in the stationary disc, toward the revolving plate. If a plate of vulcanite be excited, and then be laid against one of the paper sectors, while the disc *A* is rapidly rotated *toward the point of the sectors*, the discharging knobs being in contact, electrical induction

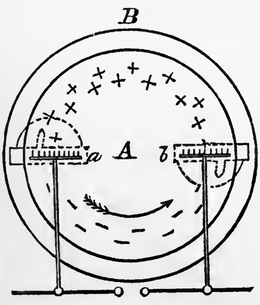
will ensue, and after a few moments the knobs may be *gradually* separated until sparks perhaps 12 or 20 inches long pass, according to the size of the machine. To produce sparks of great density two Leyden jars, *D*, *D*, with their inner coatings connected to the discharging knobs and their outer coatings connected with each other, are added.

Fig. 326.



To explain, in a very general way, the action of the machine, let *A* (Fig. 327) represent the revolving plate and *B* the stationary disc behind it, carrying the paper sectors *a* and *b*. Imagine the combs in front of *A*, and call them *a* and *b* also, remembering that the sectors are on the plate *B*, behind *A*. If now a positive charge be communicated to the *sector a*, it will act inductively upon the *comb a*, through the revolving plate, as a dielectric. Negative electricity will be induced in the *comb*, and, if it were of proper shape, would be bound. But, being pointed, the negative charge escapes to the surface of *A* and is carried around with it. The positive electricity of the comb is repelled by the process of induction to the discharging knob connected with it. Both knobs being in contact it passes to the *comb b*. From here it escapes to the front of the revolving disc, and at the same time induces negative electricity on the upper portion of the *sector b*. Because of the induction positive electricity escapes from the point of the *sector b* to the back of the revolving disc. If now the disc be revolved half-way around, the positive charge on the back of *A* will be taken up by the point of *sector a*, thus strengthening its original charge. *Sector b*, having now become charged negatively increases the flow of positive from

Fig. 327.



comb b, and *sector a*, having its charge increased, still further increases this flow. All the arrangements conspire to charge both the rear and front of the upper half of A with positive, and of the lower half with negative, electricity. The action requires that positive electricity shall flow continuously through the knobs from a to b. When sufficient potential difference between the combs has been obtained, the discharging knobs may be separated and a spark will rupture the air.

The Leyden jars serve to increase the capacity of the knobs, and thus, for a spark at a given potential difference, to increase the quantity of electricity passed.

A modification of the Holtz machine has been made by Wimshurst. The two plates, furnished with numerous sectors of tin-foil, are rotated in opposite directions. A full description is out of place here.

590. Effects of Statical Discharge.—Most electrical effects are best obtained by the use of current electricity. Those which require the high potential of statical electricity are the following:

MECHANICAL.—If a heavily charged Leyden jar be made to discharge itself through a piece of glass or card-board, it will, by the passage, pierce a hole through the piece. In case card-board is used, it will be found that there is a burr on both sides of the card. This is because of the vibratory character of the discharge.

PHYSIOLOGICAL.—If a discharge is made through a human being, the muscles which lie along its path will be strongly contracted. Those who have received very powerful shocks from electrical discharges say that the feeling is as though all the muscles had been so severely contracted as to result in spraining them. The action of the electricity is through the medium of the nerves.

HEATING.—A very sudden development of heat accompanies the spark at discharge. This can be easily shown by allowing a spark to pass to the tip of a gas-burner. If the gas be turned on, it will become ignited. If gas be not available, the spark may be passed to a spoon containing a few drops of common ether.

591. Lightning.—Water, in the process of evaporation, is supposed to become electrified. From the surface of large bodies of water multitudes of small electrified particles of moisture rise into the air, under the influence of the hot sun. These particles have a definite capacity (their radius) and a definite quantity of electricity. In the process of cloud formation these particles come into drops. Each drop receives the electricity of its component particles and has its capacity increased. The quantity on the drop equals the sum of the quantities on the particles. The

capacity of the drop is *less* than the sum of the capacities of the particles. Hence the potential on the drop is greater than it was upon the particles. In this manner clouds are formed, having large quantities of electricity at a high potential. The opposite kind of electricity is induced in the earth, and the air, acting as a dielectric, is placed under severe strain. Eventually the strain becomes too great and the air gives way. The equalization of potential, at that instant, gives what is termed a stroke of lightning. The intense heat developed by the discharge expands the air, and the rushing of cold air into the partial vacuum, thus formed, produces the sound thunder.

Sheet lightning, where a large surface is momentarily illuminated, is but the reflection from a cloud of an invisible true discharge.

CHAPTER III.

MAGNETISM.

592. Natural Magnets.—The ancients discovered that a certain black stone, abundantly found in Magnesia, had the property of attracting to it small pieces of iron. Accordingly, from their source, they called these stones magnets. Afterwards they found that, when hung by threads, a certain part of each stone always pointed north. From this property the stone received the name *Lodestone* (leading stone).

593. Artificial Magnets.—If a piece of steel be rubbed with a lodestone, it will be found to have acquired the property of attraction. Steel artificial magnets are what are employed in experiments in the laboratory.

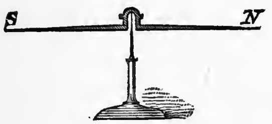
594. Poles of a Magnet.—If a steel-bar magnet be rolled in iron filings (Fig. 328), it will be observed that the attractions seem to have two common sources, two points near the ends of the bar. These two points are called the *poles* of the magnet. The straight line connecting the poles is called the *magnetic axis*.

Fig. 328.

595. Magnetic Needle.—For investigating the attractions

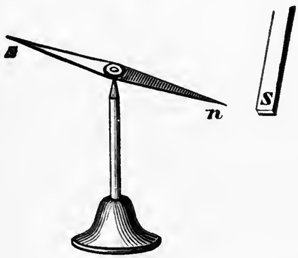
of magnets use is made of the magnetic needle. This consists (Fig. 329) of a light steel needle, which has been magnetized, and, by some suitable arrangement, is mounted upon a pivot. It is capable of moving in a horizontal plane with little friction. Left to itself it will assume a north and south direction. That end of it which points north is called the *north pole*, and the other end the *south pole*. The *compasses* sold by opticians are magnetic needles, whose north poles are generally more pointed than their south poles.

FIG. 329.



596. Attractions and Repulsions.—If a piece of iron be approached, in any manner, to either end of a magnetic needle, the needle will be attracted toward the iron. The same result will follow if either end of a magnet be approached to an iron non-magnetic needle. However, if either end of a magnet be approached to a magnetic needle (Fig. 330) attraction will follow when the adjacent poles are unlike, and repulsion takes place when the adjacent poles are of the same kind. Hence, as with quantities of electricity:

FIG. 330.



Poles of the same name repel, and those of contrary name attract each other.

597. North and South Poles Inseparable.—If any one portion of a piece of steel be touched by a north pole of a lodestone, it will be found to have developed a south pole. At the same time, however, a north pole has been developed in some other part of the steel. Again, if a bar magnet be broken at a point half-way between its poles, each of the fragments will possess two poles. Successive breaking leaves each fragment with its two different poles. The end of a fragment which had a pole before the rupture retains the same polarity afterwards. It may thus be concluded that every magnet must have two poles.

598. Magnetic Induction.—When a bar of iron is brought near to the pole of a magnet, though attraction is the phenomenon first observed, yet it is readily proved that this attraction results from a change, which is previously produced in the iron. Similar to the case of electrostatic attraction, the iron becomes a magnet

by *induction* exerted by the original magnet. By moving a magnetic needle around the iron it will be found that the end of the iron which is placed near one pole of the magnet becomes a pole of the opposite name, and the remote end a pole of the same name. Hence the adjacent, unlike poles of the iron and magnet, attract each other.

The induced magnet is more powerful the nearer it is to the inducing magnet; it is, therefore, greatest when the two bars are in contact.

Soft iron retains its magnetic properties only while under the influence of the magnet. Upon removing, it will be found to have returned to its neutral state. Had steel, or impure iron, or cast-iron been used, it would have been found to have retained more or less of the magnetic properties caused by the induction.

The inductive action may be well seen by placing iron and magnet upon a sheet of paper and then sifting iron-filings upon them. The filings will attach themselves to the iron in the same manner as to the magnet. If the magnet be now withdrawn, the filings around the iron will collapse, showing the loss of magnetic polarity.

The induced temporary magnet will, in its turn, induce temporary magnetism in a second piece of iron, and this again in a third piece. The strength, however, decreases as the pieces get farther away from the original magnet.

If the north ends of two equal magnets be touched to the opposite ends of a bar of steel, south poles will be induced in both ends of the bar. But we have seen that every south pole must have a north pole with it. Accordingly examination will reveal that the bar has two coincident north poles at its middle. Such intermediate poles are termed *consequent poles.*

599. Retentivity or Coercive Force.—The extension of the experiment of breaking a magnet (Art. 597) leads to the inference that every particle of steel is a magnet in itself. Before magnetization these molecular magnets point in all directions, and hence exert no external magnetic influence. Under the influence of induction, however, these are made to assume the same direction. Fig. 331 gives an idea of the probable arrangement of a magnetized piece of steel. The shaded ends represent the south poles of the molecular magnets. When they are all arranged as in the figure the external effect is as though there were a south pole at *S* and a north pole at *N*.

FIG. 331.

Now experiments show that tempered steel is much more difficult to magnetize than a piece of soft iron, and, after being once magnetized, retains its magnetism much better. It is, then, reasonable to suppose that the existence of foreign particles (carbon) in the steel hinders and clogs the turning of the molecular magnets from their chaotic state into regular arrangement. Once arranged, the same cause prevents a disarrangement. In pure iron the hindrance is not present. This resistance against a magnetizing or demagnetizing force is called *retentivity* or *coercive force.* As might be expected, the retentivity is modified by anything which will cause the molecules to vibrate, as hitting sharp blows with a hammer or heating to a high temperature. A magnet may be demagnetized by dropping it several times upon the floor.

The extreme amount of magnetism that could be imparted to a bar would be that which arranged all the molecular magnets in the same direction. The magnet is then said to be *saturated.* After removing the magnetizing force, however, some of the molecular magnets would of their own accord turn from line and others would follow their example in time. Hence a magnet must be kept for some time before its strength can be considered as constant. Yet a constant strength may be obtained by "cooking" the magnet. It is saturated and then placed for several hours in a bath of steam, removed and again saturated and cooked. Magnets treated in this manner are said to remain very constant.

600. Law of Magnetic Force.—Magnetic attractions and repulsions take place according to a law similar to Coulomb's law for electrical forces. Two like isolated magnetic poles of strengths m and m', d centimetres from each other, will repel each other with a force in dynes,

$$F = \frac{m\,m'}{d^2}.$$

If the poles were different, as m and $-m'$, then the value of F would be negative. A negative value indicates attraction, and a positive, repulsion.

The magnetic force will act through all substances except through magnetic substances, *i.e.*, those which are attracted by a magnet. No attraction can take place through a large iron sheet. Such a piece of iron is called a magnetic *screen.* A small magnet suspended in a hollow iron sphere cannot be deflected by an outside magnet.

601. Unit Magnet Pole.—If, in the formula for the force, given in the previous article, F and d be supposed each equal to unity, then, as in electrostatics (Art. 563),

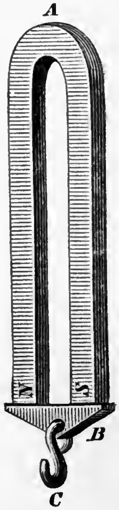
The unit magnetic pole is one that will repel an equal like pole, when at a unit's distance, with a unit force.

Of course an isolated pole cannot be obtained, for, in a magnet, it is always accompanied by an opposite equal pole, and the algebraic sum of the strengths of the poles of a magnet always equals zero.

The poles of a bar magnet are the points from which all the forces may be considered to emanate. If the strength of *one* of these poles be multiplied by the distance between the two poles, a quantity results which is termed the *magnetic moment* of the bar. In ordinary bar magnets the *pole distance* is about $\frac{5}{6}$ of the total length of the bar.

The magnetic moment of a bar divided by its weight in grams gives the *specific magnetism* of the substance of which the bar is composed. This is greatest in very hard-tempered steel. The magnetic moment divided by the volume of a magnet, *i.e.*, the magnet strength per unit volume, is termed the *intensity of magnetization* and is generally represented by the letter **I**.

Fig. 332.



602. Lifting Power.—The strength of a magnet must not be confounded with its lifting power. The latter depends upon the shape of the magnet and also upon the shape of the body lifted. A magnet bent into the shape of a horseshoe (Fig. 332) will lift about four times what it would with one end, if straight. The lifting power of a magnet grows very curiously, if the load be gradually increased from time to time.

603. Laminated Magnets.—Long, thin steel magnets are more powerful in proportion to their weight than thicker ones. Hence compound magnets are constructed, consisting of thin laminæ of steel separately magnetized and afterwards bound together in bundles. These laminated magnets (Fig. 333) are more powerful than simple bars of steel. The explanation of this fact seems to be that ordinary steel magnets are never saturated, and what magnetism they have results from molecular arrangements near the surface. The compound magnets have a greater surface and are hence stronger. Since the mutual action of the like poles in juxtaposition tends to weaken them, the strength of a compound magnet will never equal the sum of the strengths of its parts.

Fig. 333.

That the magnetism of ordinary bars is confined to the surface has been shown by placing the magnet in acid and dissolving its surface. After removal, the bar showed very little magnetic polarity.

604. Magnetic Field.—Lines of Force.—The space around a magnet where its action is felt is termed the *field* of the magnet. When several magnets are near to each other each one furnishes its own field, and superposed upon each other they form a resultant field.

The field is supposed to be permeated by magnetic *lines of force*. These lines represent the direction along which the magnetic attractions and repulsions act. An isolated magnetic pole would move along one of these lines under the attraction exerted by the field magnet. The general direction of the lines of force of a bar magnet are represented in Fig. 334.

Fig. 334.

The properties of these lines can be best discussed by considering only those which lie in a given plane passing through the magnet. Such a section is called a *magnetic spectrum*. The spectrum may be graphically represented by placing a sheet of white paper over a magnet and then sifting fine iron-filings upon the paper. A slight tapping on the paper will cause the filings to arrange themselves along the lines of force, as represented in

Fig. 335.

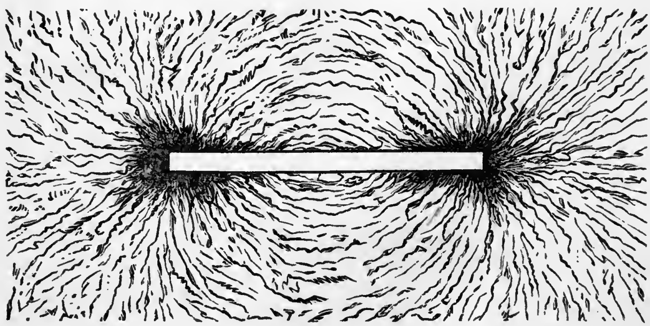


Fig. 335. With a sufficiently large figure it would be seen that every line starting from one pole finds its way, by a curved path, to the other pole.

An isolated north magnetic pole, placed upon one of these lines, would travel along it away from the north pole of the field magnet and toward the south pole. An isolated south pole would move in an opposite direction. For many reasons it is desirable to direct the lines. Hence, as represented in Fig. 334, the direction which an isolated north pole would move is taken as the positive direction.

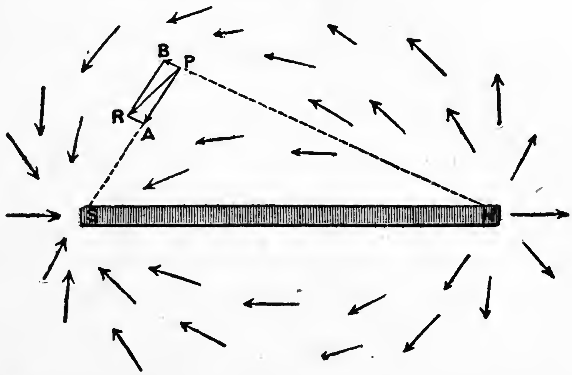
Of course it is impossible to get an isolated pole, but the undesired companion can be so far removed as not to interfere with demonstrative experiments. If a shallow glass dish, containing a little water, be placed over the magnet and spectrum shown in Fig. 335, and then a magnetized sewing-needle be floated in a vertical position, by means of a small cork, the lower pole of the needle will be so much nearer the magnet than the upper pole that it will act as an isolated pole. When placed over any line it will move along that line, however circuitous, until it reaches the pole of the field magnet, which attracts it. This experiment is much more satisfactory when the field magnet is an electro-magnet. The needle may then be placed at any desired point and commences to move only after the magnet is excited. Professor Spice sifts the filings upon a glass plate and projects the whole experiment from a vertical lantern.

If a short magnetic needle be moved around a field whose lines of force are graphically shown by iron-filings, the needle will turn until its magnetic axis coincides with the direction of the lines of force. In fact the filings themselves are little magnets, made so by induction, and tapping the paper upon which they rest serves the stead of a pivot. That the needle should so place itself is quite natural, for its north end tends to travel in one direction and its south end in an opposite direction. The result is a couple, which turns the needle until the pulls are from the same line of force, passing through the pivot.

605. Theory of the Curvature of the Lines.—In any plane passing through a magnet, *N*, *S* (Fig. 336), let *P* be an isolated unit north pole. Assume its distance from the north pole *PN*, to be twice as great as from the south pole *PS*. The unit will be repelled by the north pole with a certain force, which is represented in amount and direction by the line, *PB*. Then, according to the law of magnetic force (Art. 600), the attraction exerted by the south pole, which is only half as far away, will be four times as great, and is represented in magnitude and direction by the line *AP*. The resultant of these two forces must be the diagonal, *RP*, of the completed parallelogram; and the

unit pole would move along the line *RP*. If elementary parallelograms be constructed in this manner throughout the field,

FIG. 336.



their diagonals, when connected, will represent the lines of force.

The curvature, then, is the result of combined attraction and repulsion. The lines of magnetic force from an isolated pole would be straight, as are the lines along which gravitation acts, and the law given in Art. 600 is true for isolated poles only.

606. Fields from Several Magnets.—When several magnets are in the same vicinity, the resultant field, compounded from the separate fields of each magnet, is sometimes curiously arranged. Thus the field from two magnets, whose north and south poles are opposed to each other, is represented in Fig. 337. A short magnetic needle would be in stable equilibrium if placed in any part of this field. Fig. 338 shows quite a different field where the opposed poles are like named. A needle moved about this field would suddenly turn half round on its axis at the moment of crossing the line *cd*. When the pivot is exactly upon *cd*, the needle's south pole is attracted equally in opposite directions by the two exposed north poles. In the same manner its north pole is repelled.

FIG. 337.

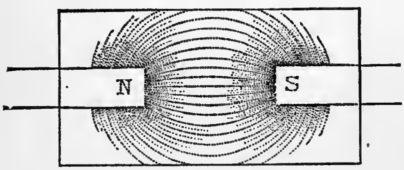
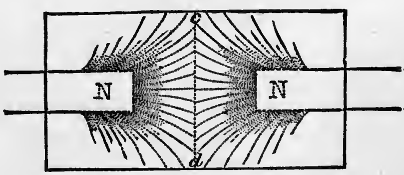


FIG. 338.



The result is that the needle places itself so that its axis is perpendicular to the axis of the field magnets.

Much may be learned by experimenting with iron-filings on variously compounded fields.

607. Strength or Intensity of Magnetic Field.—It may be reasonably supposed that each line of force exerts, along its length, a given amount of force. Hence a piece of iron, which was traversed by several lines, would be more powerfully attracted than if traversed by a fewer number. Thus a magnet pole of definite size, placed near to the pole of the field magnet, would be attracted with more force than at a distance, for the lines are closer together near the poles of the field magnet. The number of lines of force, then, which penetrate a given area, determines the relative force exerted by the field at that place. This is termed the *strength* or *intensity* of the field.

In order to compare the strengths of different fields, it is necessary to have a unit of strength. Hence

A magnetic field of unit strength is one which exerts a unit force (dyne) *upon a free unit magnet pole.*

608. Determination of the Strength of a Field.—If a magnet, suspended by a fibre, be placed in magnetic fields of different strengths, it will oscillate for a long time, and the times of oscillation will be shorter the stronger the field. This is parallel to the case of pendulum vibrations. The pendulum vibrates because of the force exerted by gravity and because of its inertia. Gravity pulls its centre of gravity as near as possible to the earth, and inertia carries it beyond this position. If the force of gravity were increased, the pendulum would vibrate quicker. In the case of a magnet, the force of the field takes the place of gravity. Now, just as the force of gravity can be measured by the time of oscillation of a given pendulum (Art. 163), so the strength of a magnetic field can be measured by the time of oscillation of a given magnet.

If $t =$ the time taken by the magnet in passing from one turning-point to the other in an oscillation, $K =$ the moment of inertia of the magnet (Art. 160), $M =$ the magnetic moment of the magnet, then the strength of the field

$$H = \frac{\pi^2}{t^2}\frac{K}{M}.$$

When the same magnet is used K and M are constant, hence

$$H \propto \frac{1}{t^2} \propto n^2,$$

where $n =$ the number of single vibrations in a second. Then if

a given magnet vibrates n and n' times per second in two fields of strengths H and H',

$$\frac{H}{H'} = \frac{n^2}{n'^2}.$$

If the values of M and K are known or determined, then the first equation gives the absolute strength of the field, provided all the quantities are expressed in proper units.

609. Hysteresis.—If a piece of iron be placed in a magnetic field, it will have two opposite poles induced in it whose strengths depend upon the strength of the field. If the strength of the field be varied from zero to a maximum, and then to zero again, there will be two times when the field will have a definite strength—once when the field is growing stronger and again when it is decreasing in strength. The strengths of the induced poles in the iron are different in these two equal fields. They will be less in the increasing field than in the decreasing. The strength of the iron's poles depends upon the iron's previous history. The iron has a tendency to remain in its previous condition and behind the field's requirements. This peculiarity of the iron is termed by Ewing *static hysteresis.*

If iron be placed in a magnetic field of constant strength, it will require a certain time before its induced poles assume constant strengths. To this property of the iron Ewing gives the name *viscous hysteresis.*

610. Number of Lines of Force from a Given Pole.—It is convenient to consider the number of lines of force passing through a given area in a field as the measure of the strength of the field. Each line may be supposed to exert a dyne of force on a unit pole pierced by it. The given area is a square centimetre and is placed so as to be perpendicular to the lines of force. *A unit field would* then *have one line passing through a square centimetre.*

Suppose now that, around a unit magnet pole, we conceive a spherical shell of one centimetre radius. From the definition of a unit pole (Art. 601) we know that the enclosed pole exerts, on another unit pole, a dyne of force at every point on this shell. The strength of the field, then, at all these points, is unity. Hence every centimetre of it is pierced by one line of force. But the whole surface of the sphere of unit radius contains 4 π centimetres. *The unit pole, therefore, sends off* 4 π *lines of force.* An enclosing surface of any size would be pierced by the same number of lines.

If the strength of the pole were 2 units, it would send off 8 π lines; or, in general,

A magnet pole, of strength m, sends out 4 π *m lines of force.* This conception of the magnetic lines has recently developed into many important theoretical conclusions, which have equally important practical applications.

With a real magnet, having two poles, it is important to remember that the lines of *induction*,* starting out from one pole, finally arrive at the other pole and thence pass through the magnet itself. Hence the number passing through a section of the magnet lying midway between the poles is 4 π m.

611. Magnetic Susceptibility.—If two magnets, with their opposite poles opposed to each other, be arranged along a common axis, and if the lines of induction be made visible by iron-filings, the resulting spectrum will be as in Fig. 339. If, now, a piece of iron

Fig. 339.

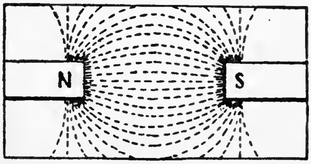
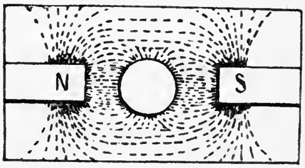


Fig. 340.



is placed between the poles, the field alters and will give, *e.g.*, the spectrum shown in Fig. 340. The lines are much more numerous where the iron is than they were before it was placed there. Had a piece of brass been used instead of iron, the field would have remained undistorted. A piece of cobalt would have produced some distortion, but not as much as the iron.

The cause of the additional lines is that the iron has, under the influence of the field, become an induced magnet and has added its lines to those already in the field.

If the field magnets were made stronger, they would send out more lines, and the iron would become more strongly magnetized and would also send out more lines. Thus, supposing that the iron does not become saturated, the strength of its pole depends upon the strength of the field and upon the volume of the iron. Suppose that the strength of the induced pole of a rectangular prism of iron is m; that the pole length equals the physical

* A line of induction differs from a line of force in that it does not change its direction on its return through the body of the magnet.

length of the iron, l; that the cross-section of the iron is s. Then the intensity of magnetization (Art. 601)

$$\mathbf{I} = \frac{m\,l}{s\,l} = \frac{m}{s}.$$

If the cross-section s be one centimetre, then $\mathbf{I} = m$, or the intensity of magnetization is equal to the strength of the induced pole. It has been found that if the strength of the field equals $\mathbf{H}$,

$$\mathbf{I} = k\,\mathbf{H},$$

where k is a constant called the *magnetic susceptibility*. It depends upon the kind of iron or other substance placed in the field. For iron, nickel, and cobalt the value is positive; for vacuum, air, and most gases is practically zero, and for bismuth, antimony, and phosphorus it is negative, though extremely small.

612. Magnetic Permeability.—In almost all of the practical problems on magnetic induction it is desirable to know the total number of lines which pass through the iron suffering induction. In the iron prism of the preceding article the total number traversing it is made up of two parts: $4\,\pi\,\mathbf{I} = 4\,\pi\,k\,\mathbf{H}$ lines from the induced pole and $\mathbf{H}$ lines from the original field. Representing this sum by $\mathbf{B}$, we have

$$\begin{aligned}\mathbf{B} &= \mathbf{H} + 4\,\pi\,k\,\mathbf{H}\\ &= (1 + 4\,\pi\,k)\,\mathbf{H}.\end{aligned}$$

It is customary to place $1 + 4\,\pi\,k = \mu$, whence

$$\mathbf{B} = \mu\,\mathbf{H}.$$

Since μ involves k, it depends upon the character of the substance under induction. For air and gases it is unity; for iron, etc., greater than unity (sometimes reaching 16,000), and for bismuth, etc., less than unity.

As $\mathbf{B}$ represents the number of lines that pass through a square centimetre of iron, and $\mathbf{H}$ the number through air, then the iron may be said to conduct magnetic lines μ times better than air. From consideration in this light μ has received the name *magnetic permeability*.

The magnetic permeability of a substance is its relative conductivity for magnetic lines of force as compared with vacuum (or air) *as a standard.*

The equations connecting $\mathbf{B}$, $\mathbf{H}$, $\mathbf{I}$, μ, and k, which have been given are true whatever be the cross-section of the iron under induction. The assumption of a square centimetre cross-section is for simplification only.

613. The Magnetic Circuit.—In the construction of most electro-magnetic apparatus it is of utmost importance that *as much as possible of the field of the magnetizing agent shall be occupied by a*

substance of great permeability such as iron. For instead of having merely the lines which can be sent through air by the agent we can just as well have the additional ones from the iron. Of course an air gap must be left somewhere in the circuit of the lines in order to introduce the body to be acted upon. But this gap should be as small as possible if a maximum effect be desired.

If the opposite poles of two straight electro-magnets be caused to attract a piece of iron, the iron fills in one gap, but the lines from the other ends pass through the air. The force of the original attraction would be much increased if the extreme ends were connected by an iron bar. This last bar sends its additional lines through the magnets and increases the force.

614. Paramagnetism and Diamagnetism. — Substances which have a permeability greater than 1 (that of vacuum) as iron, steel, nickel, cobalt, etc., are attracted by a magnet and tend to move toward it. If not allowed to move toward, but allowed to rotate, they will tend to set themselves axially with the lines of induction. These are called *paramagnetic* substances.

Substances of permeability less than unity show the opposite tendencies. They are repelled by magnets and set themselves perpendicular to the lines of force. They are bismuth, antimony, phosphorus, etc. Without making use of the term permeability we may say:

Those substances which are attracted by a magnetic pole, or which in a magnetic field tend to move from places of less to places of greater intensity, are called Paramagnetic.

Those substances which are repelled by either pole indifferently, or which move from places of greater intensity to places of less intensity in the field, are called Diamagnetic.

In order to explain the phenomena of paramagnetism and diamagnetism we have to consider that the movable parts of a magnetic circuit strive to adjust themselves so that the maximum lines of induction shall pass through the circuit. Paramagnetic substances are thus drawn into the circuit and place themselves longitudinally with the lines, while diamagnetic substances act in an opposite manner, the air furnishing more lines than if they should displace it.

The repulsion of diamagnetic substances is hard to illustrate before a large audience. A huge electro-magnet may be made to slightly repel a piece of bismuth suspended on a long, delicate fibre. Better results can be obtained by approaching a large piece of bismuth to one of the needles in an astatic magnetometer (Art. 625).

CHAPTER IV.

TERRESTRIAL MAGNETISM.

615. The Earth a Magnet.—If a needle is carried round the earth from north to south, it takes approximately all the positions in relation to the earth's axis which it assumes in relation to a magnetic bar, when carried round it from end to end. At the equator it is nearly parallel to the axis, and it inclines at larger and larger angles as the distance from the equator increases; and in the region of the poles it is nearly in the direction of the axis. *The earth itself, therefore, may be considered a magnet,* since it affects a needle as a magnet does, and also induces the magnetic state on iron. But it is necessary, on account of the attraction of opposite poles, to consider the northern part of the earth as being like the south pole of a needle, and the southern part like the north pole.

616. Declination of the Needle.—When the needle is balanced horizontally, and free to revolve, it does not generally point exactly north and south; and the angle by which it deviates from the meridian is called the *declination.* A vertical circle coincident with the direction of the needle at any place is called the *magnetic meridian.* As the angle between the magnetic and the geographical meridians is generally different for different places, and also varies at different times in the same place, the word *variation* expresses these *changes* in declination, though it is much used as synonymous with declination itself.

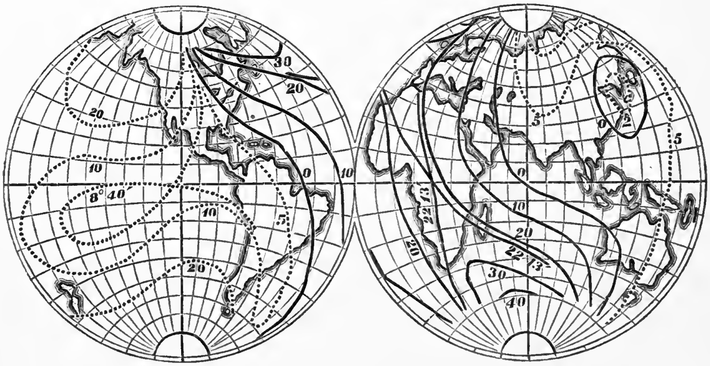
The force which causes the needle to set in the magnetic meridian is *merely directive.*

If the needle be weighed before it is magnetized and again after it has been made a magnet, no change of weight can be detected, proving that the earth's attraction for one pole is exactly equal to its repulsion of the other. This may also be shown by attaching a magnet to a cork and thus floating it upon water. It will set in the magnetic meridian but will show no tendency to move across the water toward the north, nor in any other direction. This effect is due to the earth's uniform magnetic field. The magnetic pole of the earth being practically at an infinite distance, the forces of attraction and repulsion, being equal, constitute a couple.

617. Isogonic Curves.—This name is given to a system of lines imagined to be drawn through all the points of equal decli-

nation on the earth's surface. We naturally take as the standard line of the system that which connects the points of *no declination*, or the isogonic of 0° (Fig. 341). Commencing at the north

FIG. 341.



pole of dip, about Lat. 70°, Lon. 96°, it runs in a general direction E. of S., through Hudson's Bay, across Lake Erie, and the State of Pennsylvania, and enters the Atlantic Ocean on the coast of North Carolina. Thence it passes east of the West India Islands, and across the N. E. part of South America, pursuing its course to the south polar regions. It reappears in the eastern hemisphere, crosses Western Australia, and bears rapidly westward across the Indian Ocean, and then pursues a northerly course across the Caspian Sea to the Arctic Ocean. There is also a detached line of no declination, lying in eastern Asia and the Pacific Ocean, returning into itself, and inclosing an oval area of 40° N. and S. by 30° E. and W. Between the two main lines of no declination in the Atlantic hemisphere, the declination is *westward*, marked by continued lines in Fig. 341; in the Pacific hemisphere, outside of the oval line just described, it is *eastward*, marked by dotted lines. Hence, on the American continent, in all places east of the isogonic of 0°, the north pole of the needle declines westward, and in all places west of it, the north pole declines eastward; on the other continent this is reversed, as shown by the figure.

Among other irregularities in the isogonic system, there are two instances in which a curve makes a wide sweep, and then intersects its own path, while those within the loop thus formed return into themselves. One of these is the isogonic of 8° 40′ E., which intersects in the Pacific Ocean west of Central America; the other is that of 22° 13′ W., intersecting in Africa.

In the northeastern part of the United States the declination has long been a few degrees to the west, with very slow and somewhat irregular variations.

618. Secular and Annual Variation. — The declination of the needle at a given place is not constant, but is subject to a slow change, which carries it to a certain limit on one side of the meridian, when it becomes stationary for a time, and then returns, and proceeds to a certain limit on the other side of it, occupying two or three centuries in each vibration. At London, in 1580, the declination was $11\frac{1}{4}°$ E.; in 1657, it was $0°$; after which time the needle continued its western movement till 1818, when the declination was $24\frac{1}{2}°$ W.; since then the needle has been moving slowly eastward, and in 1879, at Kew, the declination was 19° 7′ *west.*

The entire secular vibration will probably last more than three centuries. The average variation from 1580 to 1818 was 9′ 10″ annually. But, like other vibrations, the motion is slowest toward the extremes.

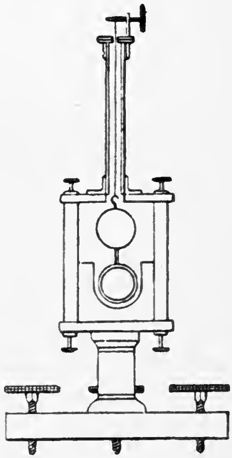
There has also been detected a small *annual* variation, in which the needle turns its north pole a few minutes to the east of its mean position between April and July, and to the west the rest of the year. This annual oscillation does not exceed 15 or 18 minutes.

619. Diurnal Variation.—The needle is also subject to a small *daily* oscillation. In the morning the north end of the needle has a variation to the east of its mean position greater than at any other part of the day. During winter this extreme point is attained at about 8 o'clock, but as early as 7 o'clock in the summer. After reaching this limit it gradually moves to the west, and attains its extreme position about 3 o'clock in winter, and 1 o'clock in summer. From this time the needle again returns eastward, reaching its first position about 10 P.M., and is almost stationary during the night. The whole amount of the diurnal variation rarely exceeds 12 minutes, and is commonly much less than that. These diurnal changes of declination are connected with changes of *temperature,* being much greater in summer than in winter. Thus, in England the mean diurnal variation from May to October is 10 or 12 minutes, and from November to April only 5 or 6 minutes.

620. Magnetometer. — In determining and observing the variation of the declination use is made of a magnetometer.

Fig. 342 represents such an instrument. It consists of a magnetized ring surmounted by a circular mirror, both being suspended by a silk fibre. The poles of the ring are at the sides and the plane of the ring, when at rest, coincides with the plane of the magnetic meridian. Any variation of the meridian is followed by a movement of the ring. The mirror, being connected with the ring, moves also. This small movement may be magnified and observed by means of a telescope and scale. The image of the scale is reflected from the mirror into the telescope.

FIG. 342.

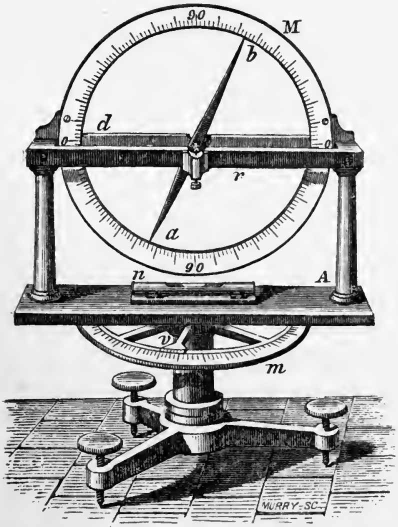


Surrounding the ring magnet is a hollowed-out piece of pure copper. This brings the magnet quickly to rest by means of the electrical currents induced in it (Art. 671) by the moving magnet.

Magnetometers are also used in determining the magnetic moment of bar magnets.

621. Dip of the Needle.—A needle first balanced on a horizontal axis, and then magnetized and *placed in the magnetic meridian,* assumes a fixed relation to the horizon, one pole or the other being usually depressed below it.

FIG. 343.



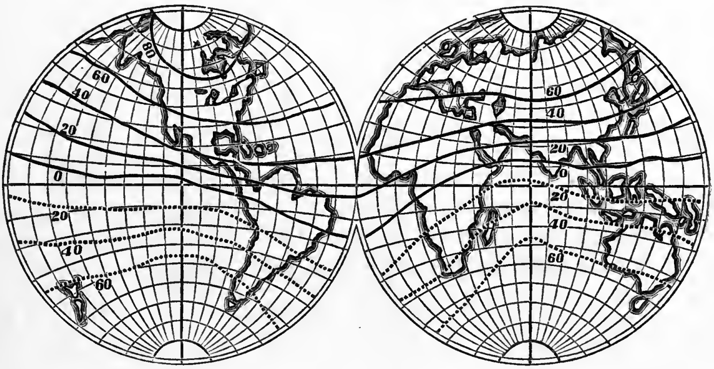
The axis of the needle must be placed very accurately at right angles to the plane of the magnetic meridian, or false indications will be given; if the axis of suspension were placed *in* the plane of the meridian the angle of depression would be 90° at all places on the earth's surface.

The angle of depression is called the *dip* of the needle. Fig. 343 represents the *dipping-needle,* with its adjusting screws and spirit-level; and the depression may be read on the graduated scale. After the horizontal circle *m* is

levelled by the foot-screws, the frame A is turned horizontally till the vertical circle M is in the magnetic meridian. For north latitudes, the north end of the needle is depressed, as a in the figure.

622. Isoclinic Curves.—A line passing through all points where the dip of the needle is nothing, *i.e.*, where the dipping needle is horizontal, is called the *magnetic equator of the earth.* It can be traced in Fig. 344 as an irregular curve around the

FIG. 344.



earth in the region of the equator, nowhere departing from it more than about 15°. At every place north of the magnetic equator the north-seeking pole of the needle descends, and south of it the south-seeking pole descends; and, in general, the greater the distance, the greater is the dip. Imagine now a system of lines, each passing through all the points of equal dip; these will be nearly parallel to the magnetic equator, which may be regarded as the standard among them. These magnetic parallels are called the *isoclinic curves;* they somewhat resemble parallels of latitude, but are inclined to them, conforming to the oblique position of the magnetic equator. In the figure, the broken lines show the dip of the south pole of the needle; the others, that of the north pole. The points of greatest dip, or dip of 90°, are called the *poles of dip.* There is one in the northern hemisphere, and one in the southern. The north pole of dip was found, by Captain James C Ross, in 1831, to be at or very near the point, 70° 14′ N.; 96° 40′ W., marked x in the figure. The south pole is not yet so well determined.

At the poles of dip the horizontal needle loses all its directive power, because the earth's magnetism tends to place it in a vertical line, and, therefore, no component of the force can operate in

a horizontal plane. The isogonic lines in general converge to the two dip-poles; but, for the reason just given, they cannot be traced quite to them.

The dip of the needle, like the declination, undergoes a variation, though by no means to so great an extent.

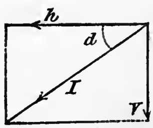
In 1576, the date of its discovery, the dip at London was 71° 50′; it increased to a maximum of 74° 42′ in 1723, since which time it has gradually decreased. In 1879 the dip at Kew was 67° 42′.

In the course of 250 years, it has diminished about five degrees in London. In 1820 it was about 70°, and diminishes from two to three minutes annually.

Since the dip at a given place is changing, it cannot be supposed that the poles are fixed points; they, and with them the entire system of isoclinic curves, must be slowly shifting their locality.

623. Intensity of the Earth's Magnetism.—The axis of the dip-needle, when placed in the magnetic meridian, coincides in direction with the lines of force of the earth's magnetic field. The magnetic force, then, acts in this inclined direction. In most magnetic determinations, however, the needle employed swings in a horizontal plane, and the force exerted upon it by the earth is only that portion of its total force which acts in a horizontal direction. This horizontal component of the strength of the field is called the *horizontal intensity* of the earth's magnetism. Let I (Fig. 345) represent the strength of the earth's field along the lines of force, *i.e.*, along the axis of the dip-needle, d = angle of dip, then h = the horizontal intensity. From the diagram it is seen that

FIG. 345.



$$h = I \cos d.$$

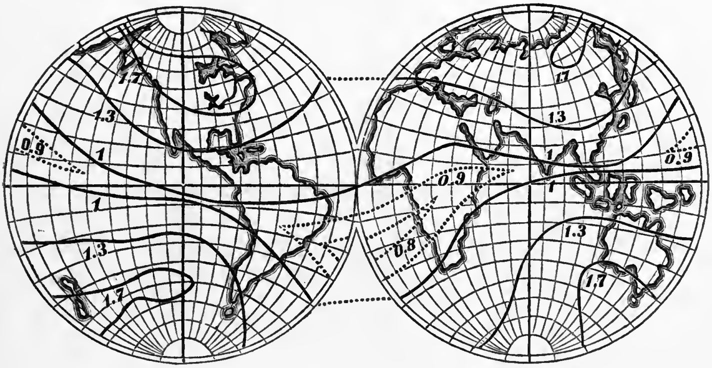
The determination of the horizontal intensity is effected after the manner described in Art. 608. Its values for places in North America are given in the following table:

HORIZONTAL INTENSITY. (C. G. S. UNITS.)

Boston	0.172
Cleveland	0.184
Chicago	0.184
Halifax	0.159
Montreal	0.147
New York	0.184
New Orleans	0.281
Niagara	0.167
Philadelphia	0.194
San Francisco	0.255
Washington	0.200

624. Isodynamic Curves.—An inspection of the table just given shows that the horizontal intensity increases as we near the equator. The strength of the earth's field in the direction of its lines of force, however, decreases on nearing the equator, as might be expected, the equator being farthest from the poles. After ascertaining, by actual observation, the intensity of the magnetic force in different parts of the earth, lines are supposed to be drawn through all those points in which the force is the same; these lines are called *isodynamic curves*, represented in Fig. 346. These

FIG. 346.



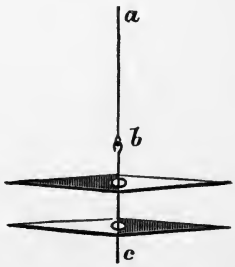
also slightly resemble parallels of latitude, but are more irregular than the isoclinic lines. There is no one standard equator of minimum intensity, but there are two very irregular lines surrounding the earth in the equatorial region, in some places almost meeting each other, and in others spreading apart more than two thousand miles, on which the magnetic intensity is the same. These two are taken as the standard of comparison, because they are the lowest which extend entirely round the globe. The intensity on them is therefore called *unity*, marked 1 in the figure. In the wide parts of the belt which they include—lying one in the southern Atlantic, and the other in the northern Pacific oceans—there are lines of lower intensity which return into themselves, without encompassing the earth. In approaching the polar regions, both north and south, the curves, retaining somewhat the form of the unit lines, are indented like an hour-glass, as those marked 1.7 in the figure, and at length the indentations meet, forming an irregular figure 8; and at still higher latitudes, are separated into two systems, closing up around two poles of maximum intensity. Thus there are on the earth four poles of maximum intensity, two in the northern hemisphere and two in the southern. The Ameri-

can north pole of intensity is situated on the north shore of Lake Superior. The one on the eastern continent is in northern Siberia. The ratio of the least to the greatest intensity on the earth is about as 0.7 to 1.9; that is, as 1 to $2\frac{5}{7}$. In the figure, intensities less than 1 are marked by dotted lines.

625. Variation in the Strength of the Earth's Field.—Astatic Needles.—The intensity of the earth's magnetism is constantly changing. These changes consist in small fluctuations about an average constant strength. Many electrical determinations require for their accuracy either that the horizontal intensity should remain constant or that its fluctuations should be taken into account. As the latter is the only alternative, a means must be had of determining, at any moment, whether the intensity has changed, and, if so, how much.

One method is to employ a magnetometer (Fig. 342), which is rendered nearly *astatic* by a supplementary bar magnet. (A needle is astatic when the earth has no directive effect upon it.) This auxiliary magnet is placed north and south, directly under, or over, the needle of the magnetometer. When placed at a proper distance above the needle, depending upon its strength, it will act upon the needle with the same force as the earth, only in an opposite direction. It will thus neutralize the influence of the earth and the needle can turn into any position. If the magnet be brought a little nearer, the needle will suddenly turn around and its north-seeking pole will point south. Now, by a little delicate manipulation, the needle may be made to point nearly east and west. In this position it is very sensitive. Any small increase in the earth's intensity will cause its north-seeking end to turn to the north, and any decrease to the south. Thus, by looking through the telescope at the mirror, any change in the intensity can be detected at any moment, and the amount of change can be arrived at by calculation.

Fig. 347.



Astatic needles are of great value in electrical measurements. Liberated from the earth's directive action they may still be affected by electrical currents. Another method of obtaining this end is shown in Fig. 347.

A compound needle, consisting of two simple needles fixed upon a wire, with their unlike poles opposed, may be suspended in any of the usual modes. If the needles are exactly equal in *all respects* the system

will be perfectly astatic. The condition of perfect equality in all the conditions is never realized.

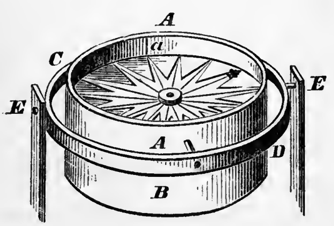
626. Magnetic Charts.—These are maps of a country, or of the world, on which are laid down the systems of curves which have been described. But for the use of the navigator, only the isogonic lines, or lines of equal declination, are essential. There are large portions of the globe which have as yet been too imperfectly examined for the several systems of curves to be accurately mapped. It must be remembered, too, that the earth is slowly but constantly undergoing magnetic changes, by which, at any given place, the declination, dip, and intensity are all essentially altered after the lapse of years. A chart, therefore, which would be accurate for the middle of the nineteenth century, will be, to some extent, incorrect at its close.

627. The Declination Compass.—This instrument consists of a magnetic needle suspended in the centre of a cylindrical brass box covered with glass; on the bottom of the box within is fastened a circular card, divided into degrees and minutes, from 0° to 90° on the several quadrants. On the top of the box are two uprights, either for holding sight-lines or for supporting a small telescope, by which directions are fixed. The quadrants on the card in the box are graduated from that diameter which is vertically beneath the line of sight.

When the axis of vision is directed along a given line, the needle shows how many degrees that line is inclined to the magnetic meridian. In order that the angle between the line and the geographical meridian may be found, the declination of the needle for the place must be known.

628. The Mariner's Compass.—In the mariner's compass (Fig. 348) the card is made as light as possible, and attached to the needle, so that the north and south points marked on the card always coincide with the magnetic meridian. The index, by which the direction of the ship is read, consists of a pair of vertical lines, diametrically opposite to each other, on the interior of the box. These lines, one of which is seen at *a*, are in the plane of the ship's keel. Hence, the degree of the card which is against either of the lines shows at once both the angle with the magnetic meridian and the quadrant in which that angle lies.

Fig. 348.



In order that the top of the box may always be in a horizontal position, and the needle as free as possible from agitation by the rolling of the ship, the box, *B*, is suspended in *gimbals.* The pivots, *A*, *A*, on opposite sides of the box, are centred in the brass ring, *C*, *D*, while this ring rests on an axis, which has its bearings in the supports, *E*, *E*. These two axes are at right angles to each other, and intersect at the point where the needle rests on its pivot. Therefore, whatever position the supports, *E*, *E*, may have, the box, having its principal weight in the lower part, maintains its upright position, and the centre of the needle is not moved by the revolutions on the two axes.

On account of the dip, which increases with the distance from the equator, and is reversed by going from one hemisphere to the other, the needle needs to be loaded by a small adjustable weight, if it is to be used in extensive voyages to the north or south.

629. **Aurora Borealis.**—This phenomenon is usually accompanied by a disturbance of the needle, thus affording visible indications of a magnetic storm; but the contrary is by no means generally true, that a magnetic storm is accompanied by auroral light. The connection of the aurora borealis with magnetism is manifested not only by the disturbance of the needle, but also by the fact that the streamers are parallel to the dipping-needle, as is proved by their apparent convergence to that point of the sky to which the dipping-needle is directed. This convergence is the effect of perspective, the lines being in fact straight and parallel.

630. **Why is the Earth a Magnet?**—Modern discoveries in electro-magnetism and thermo-electricity furnish a clew to the hypothesis which generally prevails at this day. Attention has been drawn to the remarkable agreement between the *isothermal* and the *isomagnetic* lines of the globe. The former descend in crossing the Atlantic Ocean toward America, and there are two poles of maximum cold in the northern hemisphere. The isoclinic and the isodynamic curves also descend to lower latitudes in crossing the Atlantic westward; so that, at a given latitude, the degree of *cold*, the magnetic *dip*, and the magnetic *intensity*, are each considerably greater on the American than on the European coast. This is only an instance of the general correspondence between these different systems of curves. It has likewise been noticed (Art. 619) that the needle has a movement diurnally, varying westward during the middle of the day, and eastward at evening, and that this oscillation is generally much greater in the hot season than the cold. It is obvious, therefore, that the development of magnetism in the earth is intimately connected with the tempera-

ture of its surface. Hence it has been supposed that the heat received from the sun excites electric currents in the materials of the earth's surface, and these give rise to the magnetic phenomena.

Most interesting is the hypothesis recently projected by Professor Bigelow, viz., the earth is revolving and moving in a magnetic field, which is created by the sun. According to this the earth is a magnet by induction and the variations in its magnetism are caused by differences in the strength of the field through which it is moving.

CHAPTER V.

CURRENT ELECTRICITY.

631. Electricity in Motion.—It has been seen (Art. 571) that when conductors which have a difference of electrical potential are connected together by a conducting substance, a flow, or *current*, of electricity from the higher to lower potential takes place. This current, however, lasts for an instant only, and any phenomena due directly to the flow would have to be observed during that instant. If by any means the difference of potential of the bodies could be maintained in spite of their being connected, a continuous current would be made to traverse the connecting conductor. Such a means was accidentally discovered in 1786, by Galvani, Professor of Anatomy at Bologna. After experimenting, one day, upon the effects of statical electricity on a frog's leg, he hung the moist leg, by means of a copper hook, upon an iron window-guard. He then noticed that, whenever the free end of the leg touched the guard, it gave a spasmodic twitch, as though a statical charge had been passed through it. He accordingly surmised that he had found a new method of obtaining electricity.

632. Galvanic Cells.—Galvani's discovery has developed into the *Galvanic Cell* or *Element*—an arrangement of apparatus designed to give a continuous flow of electricity.

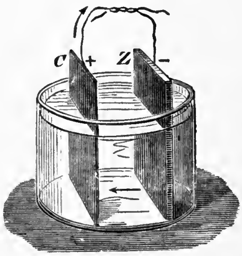
If, when two different substances are submerged in an oxidizing fluid,* one of them has a greater affinity for oxygen than the other, then a difference of potential will be set up between them. The one having the greater affinity will have a lower potential. If desirable, the substances may be considered as having become electrified—the least oxidizable positively, and the other negatively.

* For simplicity, affinity for oxygen is alone mentioned here. The principle is true for any chemical affinity.

If, now, the substances be connected by a wire, a current will flow through it from the higher to the lower potential. As long as the chemical action keeps up, the difference of potential and the current resulting from it will be maintained.

If, for example, the two substances were copper and zinc plates, and the fluid was dilute sulphuric acid (Fig. 349), the zinc, having greater affinity for the oxygen of the acid, would have a lower potential than the copper. Upon connecting them by a wire, a current would flow from the copper to the zinc. This would be a simple galvanic element.

FIG. 349.



The arrangement need not be as shown in the figure, for a zinc rod, wrapped in blotting-paper, upon which is wound bare copper wire, would, upon moistening the paper with dilute acid, give a current.

The flow from copper to zinc, in the connecting wire, is always accompanied by an equal flow from zinc to copper through the submerging fluid. (This latter flow is found necessary for the maintenance of the potential difference.) Thus, if we start at any point and follow the current, we will eventually come back to the point whence we started, *i.e.*, *a current of electricity always flows in a closed circuit.*

633. Electromotive Force.—The difference of potential set up in a galvanic element is due to an *Electromotive Force*, which is generally represented by the letters E. M. F. Its amount depends upon the nature of the two substances employed—their relative affinities for the active part of the fluid. In dilute sulphuric acid they arrange themselves in the following order:

Hydrogen,
Zinc,
Iron,
Lead,
Nickel,
Bismuth,
Copper,
Carbon,
Silver,
Platinum,
Oxygen.

Of the metals given, zinc has the greatest affinity for oxygen, and platinum the least. These two metals then would give the

greatest E. M. F. Platinum and silver would give hardly any. If two elements be constructed, using lead-zinc for one and lead-copper for the other, the current would flow out of the lead in the first case, and into the lead in the second.

The absolute electrostatic unit of potential difference is too large for practical purposes, hence a practical unit of E. M. F., called the *volt* (= $\frac{1}{300}$ electrostatic unit) is employed. The E. M. F. of copper-zinc in dilute sulphuric acid, at the instant of making first contact, is 0.921 volt.

The E. M. F. of a cell is independent of the size of the electrodes.

A copper-zinc cell of 1 sq. cm. electrodes has the same E. M. F. as one with 1,000 sq. cms.

The total E. M. F. in a circuit is equal to the algebraic sum of the separate E. M. F.'s.

Thus, if two copper-zinc cells be connected in a circuit in the order (Cu—Zn)—(Zn—Cu) one will tend to send a current in one direction, and the other in the opposite direction. The result will be no current at all.

If, in trying this experiment, one of the cells be very large and the other very small, the fact that no current flows would illustrate the fact that the E. M. F. is independent of the size of electrodes.

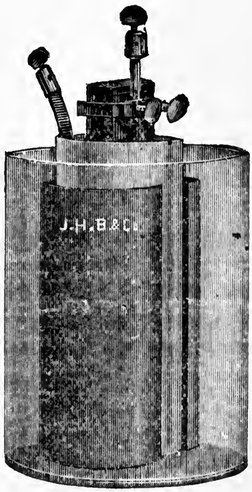
634. Polarization.—If a copper-zinc sulphuric-acid cell be connected with an electric bell (or any other current indicator) it will at first ring loudly, but will soon weaken, and finally cease to give a sound. Upon investigating the cause of this weakening it will be found that the E. M. F. has fallen from 1 volt to possibly 0.2 volt. This is because the current, which the element has sent through its own liquid, has decomposed that liquid, and hydrogen (Art. 678) has been deposited upon the copper and oxygen upon the zinc. The oxygen immediately enters into chemical union with the zinc, but the hydrogen remains in its gaseous form. The hydrogen, from its affinity for oxygen, sets up a *counter E. M. F.*, tending to send a current in an opposite direction. The resulting current is smaller than at first, and the cell is said to have become *polarized.*

635. Types of Batteries.—(A collection of galvanic cells is termed a *battery.*) Practical cells, designed for giving a constant flow of electricity, employ different methods for avoiding the counter E. M. F. of polarization. The market affords a great variety, but we need consider but three:

Bunsen's Cell.—As has been shown, the counter E. M. F. is due to hydrogen upon the electrode having the higher potential.

In Bunsen's cell this hydrogen is made to combine with oxygen furnished by nitric acid. The cell (Fig. 350) employs two different acids, which are kept separate by a porous, unglazed cup. This allows the electricity to flow, but prevents a free mixture of the acids. Outside the cup is zinc in dilute sulphuric acid; inside is carbon in nitric acid. The hydrogen, which above was deposited upon the copper, now comes off at the carbon. Instead of being allowed to exert a counter E. M. F., it is immediately oxidized by the nitric acid. On the other hand, this acid is prevented by the porous cup from violently attacking the zinc.

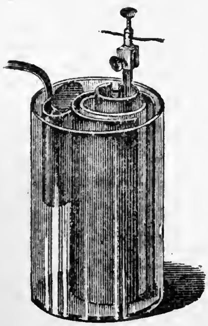
FIG. 350.



This cell has an E. M. F. of 1.8 volt, and is capable of maintaining it for a long time. It is a disagreeable cell to work with because of the nitric-acid fumes. These fumes can be avoided by substituting a solution of bichromate of potash for the nitric acid. It is also an active oxidizer; but, in time, large crystals form inside the walls of the porous cup and cause them to break in pieces.

DANIELL'S CELL.—This cell is more used than any other, in the laboratory. It also employs two liquids and a porous cup. The arrangement is (Fig. 351) zinc in dilute sulphuric acid inside the cup, and copper in copper sulphate outside. The cell's own current, instead of depositing hydrogen upon the copper, deposits copper from its sulphate. Now copper upon copper cannot alter the E. M. F. of the cell, and hence the Daniell has the most constant E. M. F. of ordinary cells. The E. M. F. depends somewhat upon the dilution of the sulphuric acid, but is very nearly 1 volt for any arrangement.

FIG. 351.

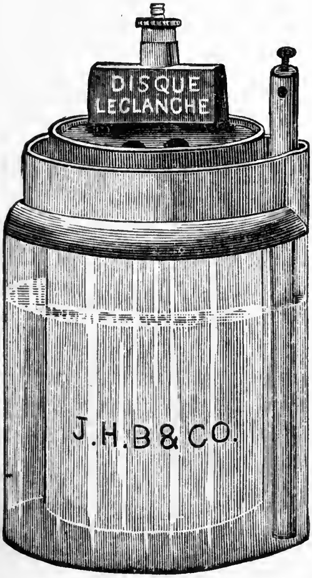


A modified form of Daniell's cell, called the *gravity cell*, is used in telegraphy. The porous cup is dispensed with, and the two liquids are kept separate by the action of gravity. The dilute sulphuric acid is floated on top of the copper sulphate.

LECLANCHE CELL.—There are more of this form of cell in use than of all others put together. They are not designed to main-

tain a constant E. M. F. for any great length of time. They are intended for purposes where a current is needed for only a few moments at most, as for electric bells or on telephone circuits. After use they regain their original E. M. F. The arrangement (Fig. 352) is zinc and carbon in a solution of sal ammoniac (NH_4Cl). An attempt is made to get rid of the hydrogen of polarization by surrounding or mixing the carbon with an oxide of manganese. This eventually oxidizes the hydrogen, but not as rapidly as the nitric acid in Bunsen's cell. Some forms of Leclanche cell employ a porous cup containing the carbon amid the manganese oxide. The E. M. F. of a fresh Leclanche is 1.5 volt.

Fig. 352.



636. Combustion of Zinc.—Nearly all batteries employ zincs for the lower potential electrode. A current flow is always accompanied by an oxidation of zinc, and the energy which accompanies the current comes from this oxidation. This is parallel to the case of a steam-engine, where the energy comes from the oxidation of the fuel under the boiler.

637. Amalgamation of Zincs.—Ordinary commercial zinc is impure. If this impurity were, say copper, and a particle should be embedded near the surface of a zinc electrode, then, upon immersing in acid, the zinc and copper would form a small cell by themselves. This would be giving a current, whether the complete cell were in use or not, and would be continually wasting zinc. This wasting of zinc, because of impurities in it, is called *local action* of the cell.

It has been found that local action can be prevented by amalgamating the zinc. This is done by dipping the zinc in acid and then in mercury. The mercury unites with the zinc and *floats* the impurities to its surface. These are then detached by the gas bubbles, which are caused by their union with the acid. The zinc of the amalgam is oxidized by the action of the battery, but the mercury remains unaffected. It is, therefore, constantly going

into combination with new zinc, as the action of the battery continues.

638. Practical Units of Current and Quantity.—As, in considering the flow of water in a pipe, we give the current a definite value of say so many gallons per hour, so we can give a definite value to the electrical current.

The quantity of water passing through any cross-section of a water-pipe of varying diameter is the same for the same time and current. Likewise

The quantity of electricity passing in the unit time through any cross-section of a simple undivided circuit is the same for the same current.

To obtain a unit for current we have only to use the unit for quantity and the one for time. Now, the absolute electrostatic unit of quantity is not of convenient size for practical purposes. Hence, a new unit, termed the *Coulomb*, is employed. It equals 3,000,000,000 absolute electrostatic units. We have, then,

The practical unit of current, the ampere, is that current which delivers one coulomb per second to any cross-section of the circuit.

639. Resistance.—All substance offers a resistance to the flow of electricity. Just as motion against resisting friction produces heat, so a current overcoming electrical resistance produces heat.

The resistance offered by a given conductor depends upon two things, viz., the character of the substance and its shape. If we represent the length of a conductor by l metres, its cross-section by q sq. mm., then its electrical resistance

$$R = s\,\frac{l}{q},$$

s being a constant depending upon the character of the substance and termed its *specific resistance.** If we assumed s, l, and q each equal to unity, we would have a unit resistance. A unit, much used in Germany, the Siemen's quicksilver unit, is defined by assuming that s for quicksilver at 0° C. is unity. Hence, *Siemen's unit of resistance is the resistance offered by a column of quicksilver* 1 *metre long and* 1 *sq. mm. cross-section, at* 0° C.

The international practical unit, the *legal ohm*, is a little larger than the Siemen's unit.

$$1\ \textit{ohm} = 1.06\ \textit{Siemen's unit.}$$

If R represents the resistance of a conductor, $^1/_R$ evidently represents its *conductivity*—the greater the resistance the smaller the

* The *absolute specific resistances* depending upon l and q being measured in centimetres, and R in absolute units, are expressed by unwieldy numbers, and a comprehension of the subject does not require their consideration.

conducting power. Accordingly, $^1/_s$ can be called the specific conductivity of a substance.

SPECIFIC CONDUCTIVITIES, $k = {}^1/_s$.

Mercury	1.06
Silver	63.
Copper	58.
Iron	7.4 to 9.5
Platinum	6.9
German silver	2.5 to 6.4
$Zn\ SO_4$ (sat. sol.)	.0000043
Pure Water	.000000000025
Glass	.0

These figures evidently represent the length in metres of a wire of 1 sq. mm. cross-section, that the resistance may be 1 ohm.

Their application can be best understood by an example. Determine the resistance of a copper wire 11.6 m. long and 0.1 sq. mm. in cross-section.

$$R = \frac{l}{k\,q} = \frac{11.6}{58 \times 0.1} = 2 \text{ ohms.}$$

Silver and copper are the best conductors we have. Because of the expense of the former, copper is universally employed on electrical circuits. In fact, some modern copper is said to conduct better than silver. Absolutely pure water is probably a non-conductor. The purest water yet obtained, if placed in a tube of unit diameter and 1 mm. long would offer the same resistance as a copper wire of same diameter, but as long as the orbit of the moon.

The influence of specific conductivity upon resistance can be prettily shown by the following experiment: Pass the current from a dynamo through an electric lamp, and, by means of two electrodes, through a vessel of rain-water. As long as the water is pure the lamp will not be illuminated. Place a few drops of sulphuric acid in the water, and the lamp will instantly commence to glow.

640. Influence of Temperature.—The resistance of conductors changes with the temperature. In all metals an increase of temperature increases the resistance. At ordinary temperatures the increase for most pure metals is 0.004 of the whole, per degree centigrade. The amount for German silver is about 0.0003.

Carbon and liquids decrease in resistance when the temperature is raised. The change per degree for liquids is between two and three per cent.

The dependence of resistance upon temperature furnishes a means of measuring the latter. A conductor of large temperature

coefficient is subjected to the heat whose temperature is to be determined, and while still in place its resistance is measured. The increase of resistance furnishes data for calculation of the temperature. By this means Professor Langley has measured the heat radiated from the moon.

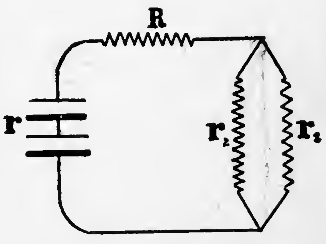
641. Ohm's Law.—The three electrical magnitudes—current, E. M. F., and resistance—are connected together by an important relation called Ohm's law. Letting E represent, in volts, the algebraic sum of all the E. M. F.'s of a circuit, R the sum of all the resistances, in ohms (of battery, conducting wires, and all instruments in circuit), then this law states, the current strength in amperes,

$$C = \frac{E}{R}.$$

The strength of the current varies directly as the E. M. F., and inversely as the resistance.

642. Divided Circuits.—Shunts.—If a current from a battery of E. M. F. $= E$ and *internal resistance* $= r$ be sent through a wire which divides at a certain point (Fig. 353) into two branches, which however reunite further on, and if the resistances of the undivided conductor and its branches are R, r_1, r_2 respectively, then the substitution of $r + R + r_1 + r_2$ in Ohm's law would not give the correct current strength. The reason for this is that the whole current does not pass through each of the branches r_1 and r_2. They each take a portion of the current, depending upon their resistances. A single conductor might be found, which, if substituted for the two, would leave the current in R unchanged. The resistance of this single conductor might be called the *equivalent resistance* of the branches. To determine this equivalent resistance it is most convenient to consider the *conductivities* of the branches. Evidently the conductivity of the single replacing conductor must equal the sum of the conductivities of the separate paths. But the conductivities are the reciprocals of the resistances. Hence we have

FIG. 353.



$$\frac{1}{R'} = \frac{1}{r_1} + \frac{1}{r_2} \therefore R' = \frac{r_1 r_2}{r_1 + r_2}.$$

The current C flowing through the undivided portion of the circuit, *e.g.*, through R, would be, by Ohm's law,

$$\frac{E}{R + r + R'} = \frac{E}{R + r + \dfrac{r_1 r_2}{r_1 + r_2}}.$$

In the same manner the equivalent resistance of any number of different paths may be determined.

When a conductor is placed so as to take a portion of the current which is passing through another conductor it is called a *shunt* and the current is said to be shunted.

Many delicate instruments for measuring electrical quantities would be ruined if the whole current passed through them. In such cases a portion of the current is shunted off from the instrument. From the known resistances of the instrument and the shunt the quantities to be determined can be calculated.

643. Ratio of Currents in Shunts.—In order to determine the portion of the current flowing in any branch of a divided circuit, we must consider that the whole current is carried by the branches as a whole. Letting $C =$ current in undivided portion (Fig. 353) and c_1 and $c_2 =$ currents in r_1 and r_2, we have

$$C = c_1 + c_2.$$

Again, bearing in mind that the difference of potential (E. M. F.) between the ends of each branch is the same $= e$, we have, by Ohm's law,

$$c_1 = \frac{e}{r_1};\ c_2 = \frac{e}{r_2}, \text{ etc.}$$

$$\therefore\ c_1 : c_2 : \text{etc.} = \frac{1}{r_1} : \frac{1}{r_2} : \text{etc.}$$

The currents carried by different branches between two points of a circuit are inversely as the resistances of the branches.

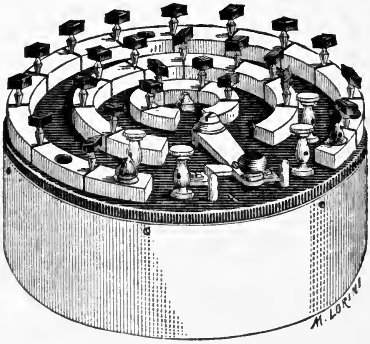
644. Fall of Potential.—If we have a battery connected through a uniform straight wire of given resistance, we may consider the potential at the zinc end to be $=$ zero, and that at the other end positive, and $=$ E. M. F. of the battery. Now, inasmuch as the resistances of equal lengths of the wire are the same, the potential at the middle of the wire equals one-half the E. M. F. At one-quarter the distance from each end of the wire the potentials are one-quarter and three-quarters of the E. M. F. The potential varies all along the wire, from zero at the zinc end to E. M. F. at the other end. If we commence at the other end we may say that

The potential falls directly as the resistance.

Of course, if the conductor were not homogeneous, *e.g.*, made

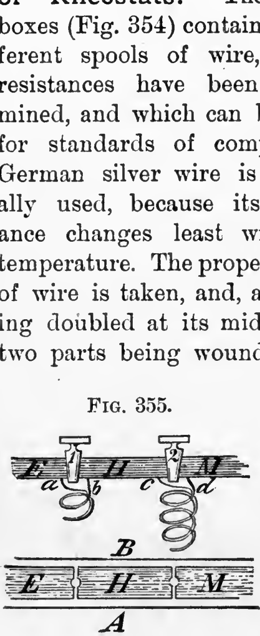
of copper and then German silver, the fall would not be the same for the same lengths. It would be more rapid in the German silver portion of the circuit than in the copper portion.

FIG. 354.



645. Resistance Boxes or Rheostats. — These are boxes (Fig. 354) containing different spools of wire, whose resistances have been determined, and which can be used for standards of comparison. German silver wire is generally used, because its resistance changes least with the temperature. The proper length of wire is taken, and, after being doubled at its middle (Fig. 355), is wound upon a spool, the two parts being wound side by side. This is indicated in the figure. The reason for this doubling is to avoid the self-induction disturbances of the wire (Art. 668). The spool, when wound, is placed inside the box and the terminals are fastened to two separate brass blocks on the top of the box. To each of these blocks is fastened one end of the two neighboring coils. In the figure, *a* and *b* of one resistance are fastened to blocks *E* and *H*. The ends *c* and *d* of the neighboring coil are fastened, one to *H* and the other to *M*. The blocks can be connected together at will by brass plugs fitting into holes between them.

FIG. 355.



Suppose, now, that the two terminals of a battery be connected with *E* and *M* respectively. If the plugs 1 and 2 be removed, the current will be obliged to traverse both of the resistance coils. If plug 1 be inserted, the current will divide between the plug and the coil. But the resistance of the plug is infinitesimal, and hence, practically, the whole current passes through it and none through the coil.

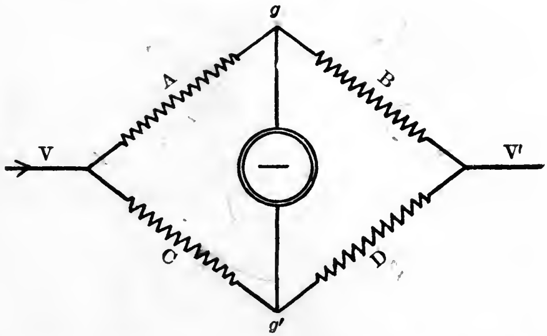
When a box of coils is inserted in a circuit, the resistance can be varied at will, by simply inserting or pulling out plugs.

646. Wheatstone's Bridge.—An important application of the preceding principles is Wheatstone's bridge. It is an arrange-

ment of apparatus by means of which resistances can be very accurately determined.

If a current of electricity arriving at V (Fig. 356) divides and

FIG. 356.



passes by two paths, A B and C D, to V', where the paths unite, then the difference of potential $(V-V')$ is acting on both paths. The potential along each path must fall from V to V'. If at any point of the path A B, the potential is g, then some point (g') of the other path, C D, can be found having the same potential. If these two points, g and g' be connected through a galvanometer or any other current detector, no current will flow, because there is no potential difference between g and g'.

Inasmuch as the fall or loss of potential along each path is proportional to the resistance, the loss in passing A must be the same as in passing C, and the resistance of A must bear the same ratio to $A + B$ as C does to $C + D$. In order that the potentials may be the same at g and g', it must be true that the resistances follow the proportion

$$A : B = C : D.$$

In Wheatstone's bridge, when no current passes through the galvanometer, *the products of the opposite resistances are equal.*

The method of determining resistances by the bridge is to place the unknown resistance in one *arm* of the bridge, as D. Known resistances are placed in A and B, and a resistance-box in C. By manipulating the plugs in C a balance can be made so that no current flows through the galvanometer. A, B, and C are known, and the required resistance

$$D = \frac{B \times C}{A}.$$

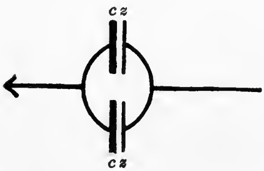
It is sometimes convenient to make C constant, and vary both A and B until a balance is obtained, A and B consisting of parts of the same straight wire of uniform diameter. The balance is

obtained by sliding the contact (g) with the galvanometer along this wire. The resistances of A and B are then proportional to their lengths.

647. Cells in Series and in Multiple Arc.—A battery of two cells can be connected to a circuit in two different manners. The copper of one may be connected to the zinc of the other (Fig. 357), and the circuit connected to the remaining zinc and copper. The cells would then be *in series.* Again, the coppers of each and the zincs of each might be connected together and the circuit connected to these short connecting wires (Fig. 358). The two cells are then said to be in *multiple arc.* Let us consider the results of these different arrangements. Represent the E. M. F. of each cell by E, and the internal resistance by r.

FIG. 357.

FIG. 358.



Evidently, when in series, the E. M. F. of the circuit is equal to the sum of the two E's, and the internal resistance of the battery is $2\,r$. If the resistance of the total external circuit be R, then the current, when the cells are in series,

$$C = \frac{2\,E}{R + 2\,r}.$$

When the cells are in multiple arc, the E. M. F. is no greater than for a single cell. The two cells are like a single cell of twice the size, and size does not affect the E. M. F. (Art. 633). The resistance, however, is only half that of a single cell, because the cross-section of the liquid, which the current has to pass, is twice as great. For two cells in multiple arc, then, the current

$$C = \frac{E}{R + \frac{r}{2}}.$$

We can extend this reasoning to any number of cells, and say,

n cells, in series, multiply the E. M. F. and the internal resistance by n, and *m cells, in multiple arc, divide the internal resistance by m, but leave the E. M. F. unaltered, it being that of a single cell.*

In general, if we have $m\,n$ cells, consisting of n groups in series, each group containing m cells in multiple arc, the resulting current will be

$$C = \frac{n\,E}{R + n\,\frac{r}{m}}.$$

With a given number of cells and a given external resistance some arrangement of the cells can be found which will give a maximum current. It can be proved that this arrangement will render *the internal resistance as nearly equal to the external as possible.*

When the external resistance is very great compared with the battery, it is advisable to get as much E. M. F. as possible. This is accomplished by placing the cells in series.

Problems.

1. An incandescent lamp takes a current of 0.7 ampere, and the E. M. F. between its terminals is found to be 98 volts: what is its resistance?

2. A current of 8.5 amperes flows through a conductor, the ends of which are found to have a difference of potential of 24 volts: what is its resistance? *Ans.* 2.823 ohms.

3. A battery, arranged in series, consists of 5 Daniell cells, each having an E. M. F. of 1.08 volt and an internal resistance of 4 ohms: what current will the battery produce with an external resistance of 7 ohms. *Ans.* 0.2 ampere.

4. Two cells of E. M. F., 1.8 volt and 1.08 volt respectively, are placed in circuit in opposition (*i.e.*, with their poles in such positions that the cells tend to send currents in opposite directions). The current is found to be 0.4 ampere: what current will be produced, if the cells are placed properly in series?

Ans. 1.6 ampere.

5. A Bunsen cell has an internal resistance of 0.3 ohm and its E. M. F. on open circuit is 1.8 volt. The circuit is completed by an external resistance of 1.2 ohm: find the current produced and the difference of potential which now exists between the terminals of the cell.

$$Ans. \begin{cases} C = 1.2 \text{ ampere.} \\ P.\,D. = 1.44 \text{ volt.} \end{cases}$$

6. Two wires of the same length and material are found to have resistances of 4 and 9 ohms respectively: if the diameter of the first is 1 mm., what is the diameter of the second?

7. The resistance of a bobbin of wire is measured and found to be 68 ohms: a portion of the wire 2 metres in length is now cut off, and its resistance is found to be 0.75 ohm. What was the total length of wire on the bobbin? *Ans.* 181.3 metres.

8. What length of platinum wire 1 mm. in diameter is required in order to make a 10 ohm resistance coil?

9. A wire m metres in length and $1/n$th of a millimetre in diameter is found to have a resistance r: what is the specific resistance of the material of which it is made?

10. A uniform wire is bent into the form of a square: find the resistance between two opposite corners in terms of the resistance of one of the sides.

11. Twelve incandescent lamps are arranged in parallel between two electric light leads. The difference of potential between the leads is 99 volts, and each lamp takes a current of 0.75 ampere: what is the equivalent resistance between the leads?

Ans. 11 ohms.

12. A battery of 20 ohms resistance is joined up in circuit with a galvanometer of 10 ohms resistance. The galvanometer is then shunted by a wire of the same resistance as its own: compare the currents produced by the battery in the two cases.

Ans. $C : C' = 5 : 6$.

13. In the preceding example determine the ratio between the currents which flow through the galvanometer before and after it is shunted.

14. How would you arrange a battery of 12 cells, each of 0.6 ohm internal resistance, so as to send the strongest current through an electro-magnet of resistance of 0.7 ohm.

15. In a Wheatstone's bridge (Fig. 356) $A = 10$ ohms, $B = 1{,}000$ ohms, and $C = 50$ ohms: what is the resistance of D, if the galvanometer shows no current? *Ans.* 5,000 ohms.

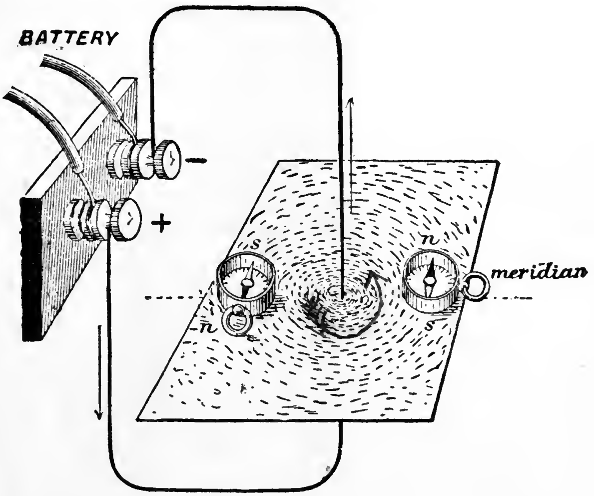
CHAPTER VI.

ELECTRO-MAGNETISM.

648. The Current's Lines of Magnetic Force. — If a wire, carrying a current of electricity, be passed through a sheet of paper, as indicated in Fig. 359, and if iron filings be sprinkled upon the paper, they will arrange themselves so as to form circles around the wire. If then a short magnetic needle be moved about the wire, it will tend to place itself tangentially to the circle passing through its centre. If the direction of the current be reversed, the needle will turn through 180°. The circles of the filings show the paths of magnetic lines of force, which owe their existence to the electrical current, just as the filings in Fig. 335 showed the paths of the lines of force of a magnet. In order to give a direction to these circular lines we must consider in what direction an isolated north magnetic pole would move. In the diagram this

would evidently be contrary to the motion of the hands of a clock. In general, to remember the directions which these lines will have,

FIG. 359.



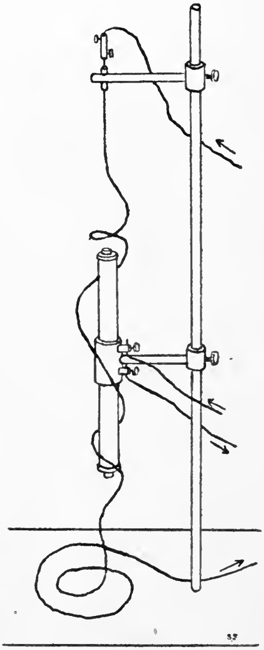
Maxwell makes use of the thrust and turn of an ordinary screw (Fig. 360). Suppose the current to flow along the axis of the screw, from the head to the point when it is being screwed into anything, and *vice versa* when it is being removed—*i.e.*, the direction of the current is the same as the direction of propagation of the screw—then the direction of the circular lines of force is the same as the motion of the circumference of the head of the screw when it is screwed in or out.

FIG. 360.

649. Effect of a Current on a Magnet.— The experiment in the preceding article shows that there is a connection between electricity and magnetism. In 1819, Oerstedt showed that a magnet tends to set itself at right angles to a wire carrying an electric current. He found, further, that the way in which the north end of the needle turns, whether to the right or left of its normal position, depends upon the position of the wire that carries the current—whether it is above or below the needle—and upon the direction in which the current flows through the wire. The position which a magnet will tend to take, when under

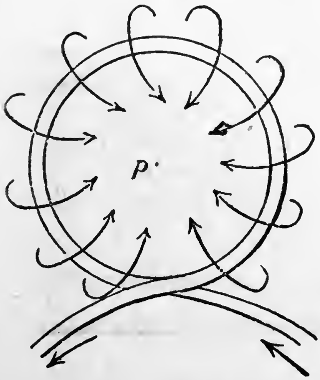
the influence of a current, can be easily determined by knowing the direction of the lines of force of both current and magnet, and by considering that the magnet will move in such a direction as to tend to bring its lines of force into the same path and direction as the lines of force of the current. Sometimes the student forgets the direction of the current's lines. In such a case let him remember that if the current flows from South to North and Over the needle, the north end of the needle will be turned toward the West, the combination being remembered by the initial letters, SNOW.

Fig. 361.



If we suppose the magnet to be fixed, and the conductor carrying the current to be movable, then the conductor will move because of the strife toward parallelism of their lines of force. Lodge illustrates this by a beautiful experiment. Send a strong current through a vertically suspended gold thread (such as is used upon military garments). Alongside the thread place, vertically, an electro-magnet (Fig. 361). Upon exciting the magnet the thread will wind itself around the magnet. Reverse the current and it will unwind and then rewind itself in the opposite direction. Complete parallelism of the lines of force is, of course, impossible, but the experiment well illustrates the tendency.

Fig. 362.



The movement of a needle under the influence of a current furnishes a convenient means of determining the direction in which the current is flowing.

650. Solenoids.—If a wire which carries a current be bent into a circle, all the lines of force will emerge from one side of an imaginary disc bounded by the loop (Fig. 362) and bending around the wire will enter the opposite side. The loop, because of the current, will be magnetically equivalent

to a disc magnet having north polarity on one side and south polarity on the other. In the diagram an isolated north pole placed above the surface of the page would be attracted toward *p*, as though it were a south magnetic pole. If the wire is coiled into the shape indicated in Fig. 363, it is termed a *solenoid* or *helix*. Upon passing a current, the lines of force, from their mutual action, take the paths indicated in the figure. A solenoid, when traversed by a current, has the same magnetic effect as a bar magnet whose axis coincides with the axis of the solenoid. Solenoids exhibit all the properties of magnets—attract pieces of soft iron, attract and repel magnets or other solenoids, and, if suspended by non-restraining quicksilver contacts, as in Fig. 364, will turn into the earth's magnetic meridian.

Fig. 363.

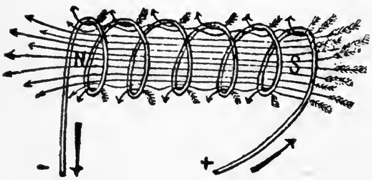
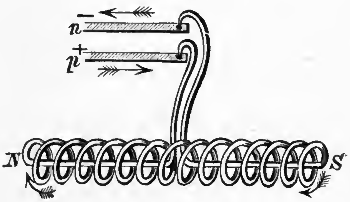


Fig. 364.



651. Ampere's Theory of Magnetism.—Because of the like actions exerted by solenoids and magnets, Ampere concluded that the permanent magnetism of steel owed itself to circular molecular currents of electricity, as shown in Fig. 365. He showed that the resultant of these many molecular currents was equivalent to surface solenoidal currents, as indicated in Fig. 366. In the interior of the magnet currents on contiguous molecules are running in opposite directions, and accordingly neutralize each other's magnetic effects. Half of the currents on the surface molecules are not neutralized, and the combined effect is the same as a surface solenoidal current.

Fig. 365.

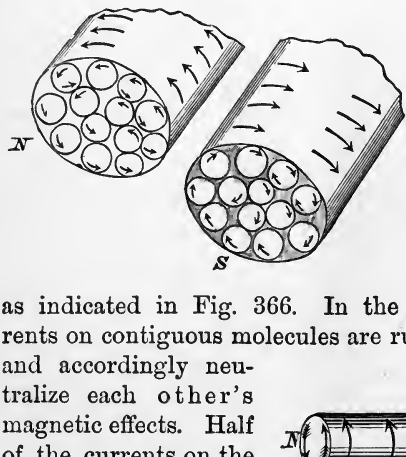


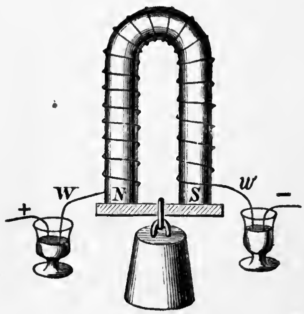
Fig. 366.

It should be remembered that looking at the north end of a magnet, end on, the amperian currents run counter-clockwise.

652. Electro-magnets.—We have seen (Art. 611) that when a piece of iron is placed in a magnetic field, it becomes an induced magnet and it adds lines of force to the field. Now, if an iron core be inserted into a solenoid, it becomes a magnet under the influence of the solenoid's field, and, because of its much greater permeability than air (Art. 612), adds many lines of force to the field. Such a combination is termed an *electro-magnet.* An electro-magnet differs from an ordinary one in that the instant the exciting current is removed the electro-magnet loses its magnetism.

The intensity of the field which a given solenoid can produce is limited only by the strength of the current traversing it. If the current strength is doubled, the strength of the field is doubled. The iron core, upon being inserted, multiplies the strength of the field by a certain factor (the permeability of the core, see Art. 612). Now, if the permeability of iron were constant, there would be scarcely any limit to the strength which could be given to an electro-magnet. But as the iron reaches the point of saturation its permeability decreases toward unity. As it is, electro magnets can be made many times more powerful than permanent magnets.

FIG 367.



A common form of electro-magnet is schematically shown in Fig. 367. The solenoid with its core is bent into the form of a horseshoe. An actual magnet would be wound with many more turns of wire, which must, of course, be insulated from the core. Upon passing a current, a heavy weight can be suspended, and this will detach itself as soon as the current is discontinued.

653. Magneto-motive Force.—In the practical construction of electro-magnetic apparatus it is often desirable to obtain a maximum number of lines of force in a given region. This region is to be occupied by some movable *armature* or object, to be subjected to the field's influences. Let us consider how this can be obtained when this region is the space between the poles of an electro-magnet. Evidently by increasing the number of lines generated by the current and adding as many lines as possible to these by proper selection of materials and shape of the electro-magnet.

The number of lines originally produced will increase with the current strength which flows through the solenoid or coil. It will also increase with the number of the loops of the wire in the coil—for each loop will add the same number of lines to those already traversing the axis of the coil. Accordingly we must employ as strong a current and as many turns of wire as possible. Remembering that the magnetic permeability of a substance is the same as its conductivity toward lines of force, it is desirable that all the space which is traversed by lines of force, except the portion which is to be employed for the movement of the object to be subjected to the field's influence, should be occupied by a substance of maximum magnetic permeability, *i.e.*, by the best soft iron.

Now we can obtain a law for the flow of lines of magnetic force exactly like Ohm's law (Art. 641) for current flow. Call the source of the lines the *magneto-motive force* (*M. M. F.*); call the reciprocal of the conductivity the *magnetic resistance* (*R*); then the magnetic flux or number of lines which pass through the axis of the coil

$$N = \frac{M.\,M.\,F.}{R}.$$

Evidently the *M. M. F.* is a function of the current strength (c) and the number of loops (n) made by the coil wire. It can be shown mathematically that if c is expressed in amperes, and N is to be obtained in absolute units, the $M.\,M.\,F. = \frac{4\,\pi}{10}\,n\,c$. The magnetic resistance is subject to the same law as electrical resistance (Art. 639). Increase the length l of the path to be travelled by the lines and the resistance is increased. It is decreased by increasing the cross-section q, and decreases with increase of magnetic permeability μ, so that the resistance

$$R = \frac{l}{\mu\,q}.$$

Introducing these values in the equation for the flux, we obtain

$$N = \frac{4\,\pi\,n\,c}{10\,\dfrac{l}{\mu\,q}}.$$

This formula is of great importance and has been of great service in the designing of efficient electro-magnetic machinery, *e.g.*, dynamos and motors. To understand the application of it, let us refer to Fig. 367. The region where maximum flux is desired is the bottom of the horseshoe where the armature and the weight attached to it are suspended. The flux will be increased by increasing the current (c), the number of turns of wire (n), the cross-sections (q) of the core, the armature and the air gaps between the

armature and the poles, by increasing the permeability (μ) of the core and armature, and by decreasing the average lengths (l) of the core, the armature, and the air gaps.

When it is considered that the permeability of iron is much greater than that of air, it will be seen that the force of attraction would be greatly lessened if a piece of the iron core were removed from the top. The force exerted by a horseshoe electro-magnet is much greater than that exerted by two parallel straight electro-magnets corresponding to the two legs of the horseshoe.

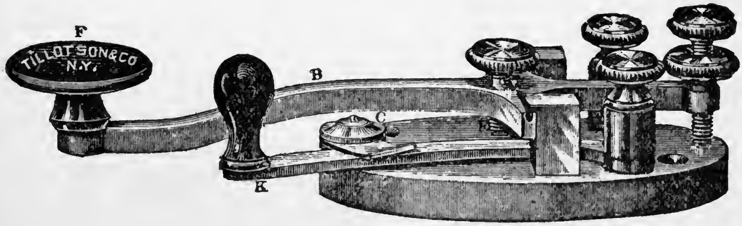
654. The Morse Telegraph System.—The fact that an electro-magnet loses its magnetism as soon as the exciting current is discontinued, was made use of by Professor Morse in the construction of his system of electric telegraph. In this system an operator at one station can, by making and breaking a current of electricity which traverses a wire to a second station, produce or destroy, at will, the magnetism of an electro-magnet in the second station. This electro-magnet is a part of an instrument called a *register*, which will be described later. According as the magnet is excited for a longer or shorter interval, the register marks upon a moving band of paper a series of dashes or dots. These may be combined so as to serve as an alphabet.

The Morse circuit has four elements: A *battery* to produce a current; a *key* to manipulate the current; a *register* or *sounder* to record the current thus manipulated; and a *line* to convey the current.

The battery generally employed is a modification of the Daniell's type, called the Gravity Battery (Art. 635). Dynamos are, however, rapidly supplanting them in the large telegraph systems.

The *key* for manipulating the current consists of a *lever*, *B* (Fig. 368), and *anvil*, *C*, both of brass, and insulated from each

FIG. 368.



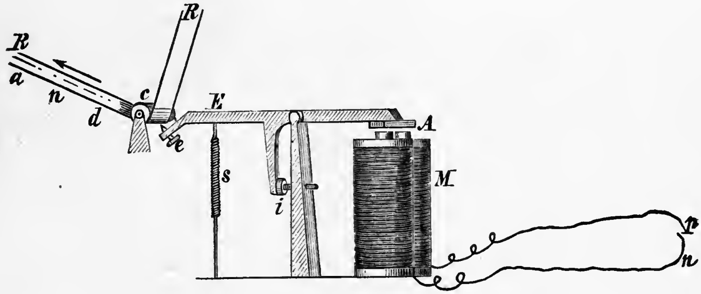
other. The anvil is connected to one terminal of the line, say from the battery, and *B* to the other terminal, where it leaves for the receiving station. The end of *B* is depressed by the finger of

the operator on the insulating button *F*, and is raised by the spring *E*, when the pressure is removed. The former movement closes the circuit, the latter opens it, and by a succession of these the message is sent. When the key is not in use, the brass bar *K*, hinged to the base of *B*, is pressed into contact with *C*. This closes the circuit so that other operators on the line may have a continuous circuit when they desire to send a message. When not in use, the line is traversed by a current.

The *register* for recording the message on paper is constructed as follows:

The lever *E* is furnished with a *style e* (Fig. 369), directly over which is a groove on the surface of a solid brass roller *c*. Between *c* and *e* is a long paper ribbon *R R*. Attached to *E* is a soft iron armature *A*, placed *above* the magnet *M*, and furnished with a

FIG. 369.



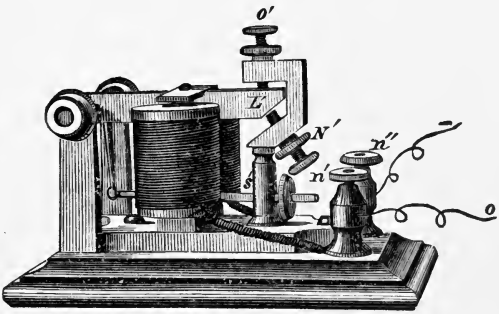
spring *s* to raise it as far as the screw *i* allows when it is not attracted by *M*. When the circuit is closed, *A* is attracted and *e* rises and forces the paper into the groove, producing a slight elevation on its upper surface. The ribbon is pulled along at a uniform rate in the direction of the arrow by clockwork (not shown in the figure), so that when the circuit remains closed for a little time, a *dash* is marked on the paper by *e*; when it is closed and instantly opened, the result is a *dot*—or rather a *very short dash*. *Spaces* are left between these whenever the circuit is opened. Combinations of these *dots*, *dashes*, and *spaces*, all carefully regulated in length, compose the letters of the alphabet. Spaces are also left between the letters, and longer ones between words.

By lengthening the circuit wire, it is evident that the person who sends the message at *n p*, and the one who receives it at *E*, may be miles apart, and the transmission will be almost instantaneous, owing to the rapid passage of the current.

It has been found that the ear is sufficiently accurate to allow of the dispensing with the register, as used by Morse. Instead of

it a *sounder* is employed. In this the end of the lever L' (Fig. 370), instead of being furnished with a style, is made to strike against

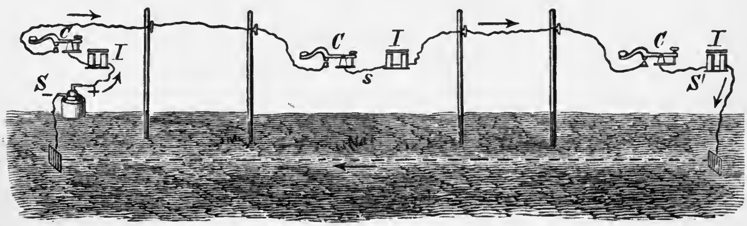
Fig. 370.



the two screws, N', O'. The downward *click* is a little louder than the upward one, and so the beginning and end of each *dot* or *dash* are distinguished from each other. Many operators learn from the first to *read by the ear*, and have never used a register.

For a *line* it was at first supposed that a complete metallic circuit was necessary, hence a return wire was employed. But this was rejected when it was found that the earth could be used as a part of the circuit, as shown in Fig. 371, in which the dotted line and arrow beneath the surface are not intended to convey the idea that a current actually flows from one earth-plate to the other, but

Fig. 371.

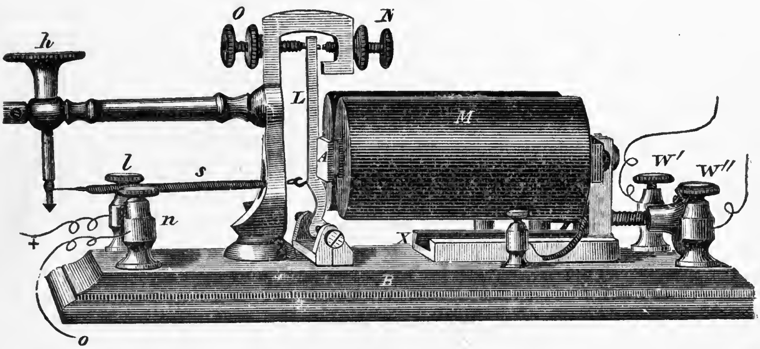


that a complete circuit is formed, the earth acting the part of an infinite reservoir of electricity. S and S' are the terminal stations, and s is one of the way stations which may occur anywhere along the line. At every station both a key, C, and sounder, I, are introduced into the circuit, so that messages can be both sent and received.

655. The Relay.—When a telegraph line is very long, its resistance is high and the leakage, because of insufficient insula-

tion, is great. Hence a current sufficiently strong to satisfactorily operate a register or sounder cannot be economically sent through it. Accordingly use is made of a *relay*. In this instrument (Fig. 372) the line current entering at W' and leaving at W'' excites the electro-magnet M. This attracts the armature A of the delicately adjusted lever L. The adjustment is obtained by regulating the tension exerted by the spiral spring s. During the passage of a current along the line, the lever L plays lightly to and fro, but with insufficient strength to act as a register or sounder. It can, however, be made to act as a *key* for a *separate local circuit* in the receiving office. One terminal of this local circuit, which contains a sounder and battery, is connected by the binding-post l with the

FIG. 372.



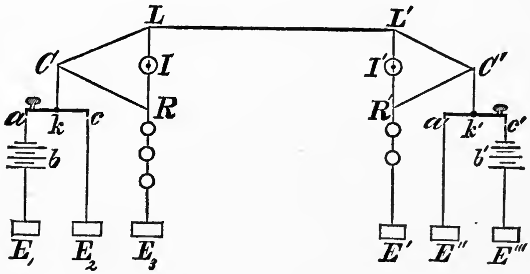
lever L. The other, through n, is connected with the screw N. When the distant operator closes his key the armature A causes the lever L to close the local circuit at N. When the distant operator opens his key, the spring s opens the local circuit. Thus the moving lever of a relay acts as a key for a local circuit.

Evidently the relay may be used for *repeating* a message on another long circuit.

656. Duplex Telegraphy.—In the Morse system just described evidently but one message can traverse the wire at the same time. If two could simultaneously traverse it, the earning capacity of the line would be doubled. This feat can be accomplished, and is termed *duplex* telegraphy. A simple duplex system, employing the principle of Wheatstone's bridge (Art. 646), is shown in Fig. 373, which represents two stations connected by the line wire $L L'$. $C L R$ is a Wheatstone bridge, modified to suit the conditions of the case, I the sounder, R resistance coils, k a key working upon the centre and having forward and back con-

tacts at a and c, b the battery, and E the earth connections. The same letters, accented, represent like parts at the second station.

FIG. 373.



When not in use the keys make back contact by the action of a spring. The *ratio* of the resistance $C\ R$ and $R\ E_3$ is made equal to that of $C\ L$ and the line wire $L\ L'$, *including the back contact earth connection* at the second station. When thus balanced any current arriving at C, which, dividing, passes through $C\ L\ L'$ and $C\ R\ E_3$, will maintain the points L and R at the same potential.

If now, a' being closed, a be closed, a current will flow through a and k to C, where it will divide, one part going to earth through R and E_3, and the other through $L\ L'$. As the potentials were made equal at L and R, no current will pass through the indicator I; that part of the current which flows through $L\ L'$ divides at L', part going through $C'\ k'\ a'$ to E'', and part through I' (giving signal) and R' to E'. Thus the closing of a gives a signal at I' but none at I.

If now the second operator should close his key while a was closed, a current from b' would flow through c' and k' to C', where it would divide, part going to earth through R' and E' (joining the current already flowing through from $L\ L'$), and part would flow to L' and oppose the current from the other station; this opposing current will have the same effect as increased resistance in the line wire $L\ L'$, and hence the balance $C\ L\ R$ will be disturbed, the potential of L rising above that of R, and resulting in a current from L through I to R, giving a signal at I. Thus the register at each station will respond to the key of the other, and only to that, whether one or both operators be signalling.

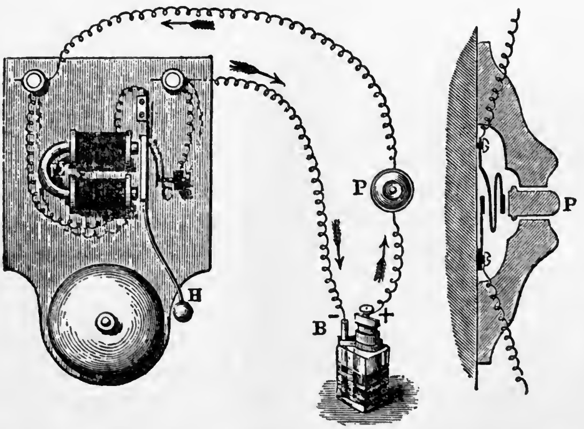
The above explanation of the principle of this particular mode of sending simultaneous messages in opposite directions on a single wire, does not pretend to describe the *actual* arrangement of wires or earths in use. For a full description of the various modes of duplex and quadruplex telegraphy the student is referred to works on practical telegraphy.

657. Atlantic Telegraph Cable.—This cable stretches a distance of 3,500 miles, and from the nature of the case is a continuous wire, so that it cannot be advantageously worked by the Morse apparatus. The indicator employed is a sensitive galvanometer needle, which is made to oscillate on opposite sides of the zero point by the passage through it of currents in opposite directions. But to reverse the direction of the current throughout the whole length of the cable is a slow process. *For the cable is an immense Leyden jar*, the surface of the copper wire (amounting to 425,000 sq. feet) answering to the *inner* coating, the water of the ocean to the *outer*, and the gutta-percha between the two to the *glass* of an ordinary jar. A current passing into it is therefore detained by electricity of the contrary kind induced in the water, and no effect will be produced at the farther end until it is *charged.*

This very circumstance, at first considered a misfortune, is now taken advantage of in a very simple and ingenious manner to facilitate the transmission of signals. The current is allowed to pass into the cable till it is *charged*—then, *without breaking the circuit*, by depressing a key for an instant, a connection is made between it and a wire running out into the sea; that is, between the inner and outer coatings. *This partially discharges it*, and the needle at the other end is deflected. When the key is raised the discharge ceases, the current flows on as before, and the needle is deflected in the opposite direction.

658. Electric Bells.—The ordinary electric house bell consists of an electro-magnet, which moves a hammer backward and

Fig. 374.

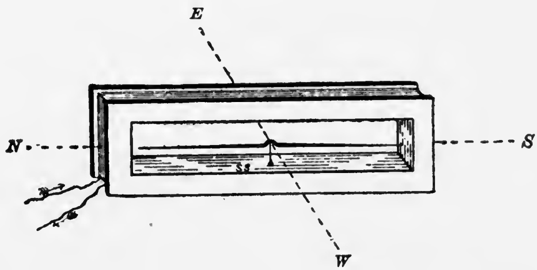


forward by alternately attracting and releasing it, so that it beats against a bell. The arrangements of the instrument are shown in

Fig. 374. A current from a battery (usually of the Leclanche pattern), after traversing the electro-magnet E, enters a spring attached to the armature and bell-hammer. It leaves the spring by an adjustable screw, C, and returns to the battery. When it flows it excites the magnet which attracts the armature and causes the hammer to hit the bell. In moving toward the magnet the contact at C has been broken, and the magnet losing its magnetism allows the armature to spring back so that the contact is renewed. This operation is repeated, the current repeatedly making and breaking itself. One of the wires from the battery to the bell is cut at the point P, and a push button is inserted. This is shown in section to the right. An insulating knob, P, when pressed, brings a spiral spring, which is connected with one end of the cut wire, into contact with the other end. The circuit being closed thus, the bell commences to ring.

659. Galvanometers.—These instruments are employed in the laboratory for the determination of nearly all electrical magni-

FIG. 375.



tudes. They serve to detect the presence of electrical currents and to determine their strengths and directions. The principle of their action is electro-magnetic. Suppose a magnetic needle (Fig. 375), free to move about a pivot, to lie in the direction of the earth's magnetic meridian. Suppose further, that it be surrounded by a coil of wire, whose windings are parallel to the axis of the needle. If, now, an electrical current be sent through the coil, it will develop magnetic polarity in the coil so that, *e.g.*, its east side will be equivalent to a north pole and its west side to a south pole. The needle will, under this influence, tend to place itself in an east and west direction. It will not quite attain this direction, for it is influenced by the earth's magnetism at the same time, and this tends to keep it in the meridian. Upon reversing the direction of the current, the polarities of the sides of the coil become reversed, and the needle turns so that its poles project from opposite sides

of the coil. The side toward which the north end of the needle turns determines the direction of the current in a given galvanometer. The angle through which the needle is deflected determines the strength of the current flowing.

Tangent Galvanometers.—If the wire of a galvanometer be wound on the circumference of a ring, whose diameter is at least twelve times the length of the needle at its centre, the strengths of currents causing different deflections will be proportional to the *tangents* of the corresponding angles of deflection. Such an instrument is called a *tangent galvanometer.* The reason for having a large diameter for the coil is that those of its lines of force, which are cut by the short needle in its excursions, are then straight and perpendicular to the earth's lines. The magnet's pole is thus moved under the influence of two forces, which act continuously at right angles to each other. The law of the tangents then follows.

Reflecting Galvanometers.—In refined laboratory measurements the determination of a needle's deflection, by observing the movement of a pointer over a divided scale, is inaccurate and inconvenient. Instead, a small mirror is attached to the magnet and the deflections are measured by the different divisions of a stationary divided scale, which are reflected from the mirror into a stationary telescope. The arrangement is shown in Fig. 319.

A method, much used in England, is to have the mirror reflect a ray of light from a small hole in an opaque chimney of a lamp upon a stationary scale. The method is very inconvenient, as it requires the observations to be made in a darkened room. The accuracy to be obtained is not as great as by means of a telescope and scale.

Ballistic Galvanometers.—In many determinations it is required to measure currents which last but for an instant, or to measure *quantities* of electricity. The difficulties connected with these determinations are much lessened if the time required by the galvanometer needle to make a single oscillation be very great, as compared with the time occupied by the electricity in passing. Thus galvanometers whose needles have periods of from five to twenty-five seconds are used, and are called *ballistic galvanometers.*

Differential Galvanometers.—These instruments are supplied with two sets of coils, which are so placed that they will produce the same electro-magnetic effect upon the single needle, providing they be traversed by currents of the same strength and direction. By means of this instrument a current in one coil may be brought to a given strength by being made to neutralize the effect upon the needle from another current, which is of constant (the required) strength and passes through the other coil in an opposite direction.

CHAPTER VII.

ELECTRO-DYNAMICS.

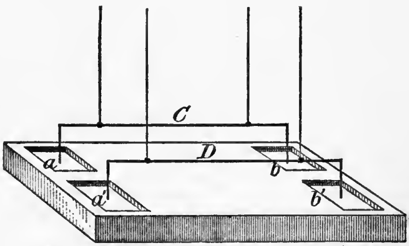
660. Movement of Conductors Carrying Currents.—In the preceding chapter it has been shown that a conductor carrying an electrical current, and placed in the vicinity of a magnet, tends to move the magnet, so that the lines of force from each may become parallel, or, if the magnet be stationary, the conductor strives to move, to attain the same end. As might be expected, two neighboring conductors, while traversed by currents, tend to move so as to render their lines of force parallel.

Without any knowledge of the existence or properties of lines of force, Ampere, in 1821, arrived, by experiment, at the following laws, which could easily have been predicted by such a knowledge.

661. Parallel Currents.—

1. If galvanic currents flow through parallel wires in the *same direction*, they *attract* each other; if in *opposite directions*, they *repel* each other. These effects are shown by suspending wires, bent as in Fig. 376, so that their lower ends may dip into four separate mercury cups, *a*, *b*, *a'*, *b'*, by means of which connection between the wires *C* and *D* and the battery may be readily made. The suspending threads should be two or three feet long, and the mercury cups should be large enough to allow considerable lateral movement of the wires. If simultaneous currents be sent through the two wires *C* and *D*, in the same direction, the wires will move toward each other; if currents be sent through the wires in opposite directions at the same time, they will separate more widely.

Fig. 376.



Hence, when a current flows through a loose and flexible helix, each turn of the coil attracts the next, since the current moves in the same direction through them all. In this way a spiral suspended above a cup of mercury, so as to just dip into the fluid, will vibrate up and down as long as a current is supplied. The weight of the helix causes its extremity to dip into the mercury below it; this closes the circuit, the current flows through it, the spirals attract

each other, and lift the end out of the mercury; this breaks the circuit, and it falls again, and thus the movement is continued.

2. If currents flow through two wires near each other, which are free to change their directions, the wires tend to become parallel to each other, with the currents flowing in the same direction. Thus, two circular wires, free to revolve about vertical axes, when currents flow through them, place themselves by mutual attractions in parallel planes, as in Fig. 377, or in the same plane, as in

Fig. 377.

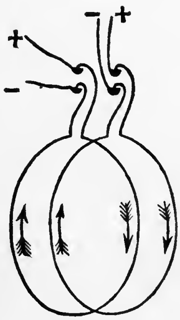


Fig. 378.

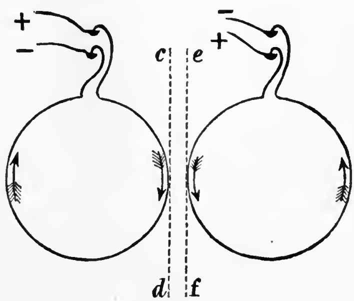


Fig. 378. In the latter case, we must consider the parts of the two circuits which are nearest to each other as small portions of the dotted straight lines, *c d* and *e f*.

It appears, therefore, that *galvanic currents, by mutual attractions and repulsions, tend to place themselves parallel to each other in such a manner that the flow is in the same direction.*

The force exerted between two parallel portions of circuits is proportional to the product of the current strengths, to the length of the portions, and inversely proportional to the distance between them. The force exerted by each current acts in a direction perpendicular to the direction of the current.

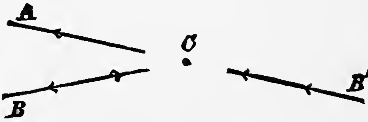
662. Currents not Parallel.—*Currents, both of which flow toward a common point, or both of which flow away from a common point, attract each other.*

If one of two currents flows toward, and the other away from a common point, the two currents repel each other.

These cases are evident deductions from the preceding paragraph. Suppose the two currents (Fig. 379) to flow in *A* and *B* as though they came from *C*, then the tendency of the wires *A* and *B* is towards parallelism, and as we suppose the currents to flow from the direction *C*, the wires must tend to move toward each

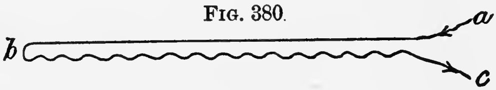
other in order to become parallel. The same effect would be produced if the currents in A and B were to flow towards C. But if the current in A flows *from* the direction C, and that in B *towards* the point C, then the tendency of the wires to become parallel, with the currents flowing in the same direction, causes B to revolve about C as a centre till it reaches the position B', and then the condition that the currents shall flow in the same direction will be fulfilled. It is not necessary that we should regard A and B as lying in the same plane.

FIG. 379.



A sinuous current produces the same effect as a straight current having the same general direction and length. If a conductor, having one portion sinuous and the other straight, be bent as in Fig. 380, so that the current may flow from a to b through the

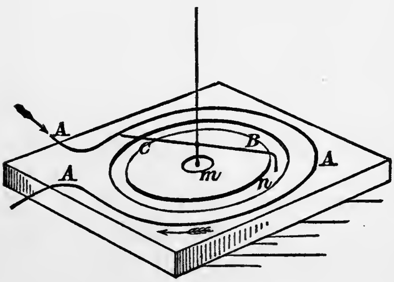
FIG. 380.



straight part, and from b to c through the sinuous part, the two portions of the current thus flowing close together in opposite directions, the joint electro-dynamic effect upon a movable conductor parallel to a b will be inappreciable.

663. Continuous Rotation Produced by Mutual Action of Currents.—Suppose a continuous current to flow through a wire A, as indicated in Fig. 381, and that a wire B, so bent as to dip into the mercury cup m at one end, and into the annular mercury trough n at the other, be suspended at the middle, a counterpoise, C, keeping it balanced.

FIG. 381.



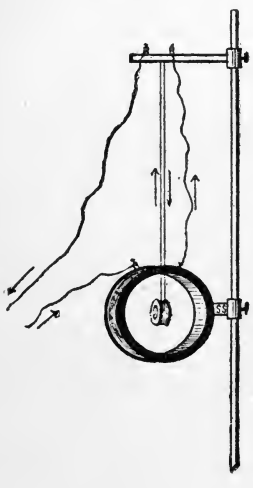
If, now, a current be made to flow from the cup m, through B, and thence out again by means of the mercury contact in n, the wire B will rotate in a direction opposite to that of the current in A; for the current in B, and that in the part of A to the right of n, are both flowing towards n and hence attract, while the current in B and that part

of the current in A immediately to the left of n are flowing in directions to cause repulsion.

A beautiful experiment, illustrating continuous rotation, is to place a round, shallow dish, containing mercury, on the pole of a vertical, straight electro-magnet. Excite the magnet and dip the terminals of a circuit, carrying a strong current, into the mercury at the centre and side of the dish respectively. A portion of the mercury carries the current from the centre to the edge of the dish. In doing so it is made to rotate by the action of the lines of force from the magnet. As soon as it has rotated a new portion of the mercury is made to carry the current. This, in turn, gives way to another portion, and the whole body of mercury is soon set into rapid rotation. Centrifugal force, resulting from the rotation, causes the mercury to heap up around the edges of the dish, and to be depressed at the centre.

664. Electro-dynamometer.—This instrument, invented by Weber, is used for measuring the strengths of electrical currents. Its action depends upon the electro-dynamic attractions discussed in Art. 661. The principles of its construction are shown in the crude apparatus represented in Fig. 382. This consists of a fixed hollow coil of wire, in the centre of which is suspended another smaller coil. The suspension is made by means of two fine parallel wires, placed one or two millimetres from each other. The upper ends of these wires are connected to two insulated binding-posts, and the lower ends are connected with the terminals of the suspended coil. The suspension is so arranged that, when no current is passing through the dynamometer, the planes of the two coils are perpendicular to each other. If, now, a current of electricity be sent through the apparatus (in the following order · through the external coil, down one suspension wire, through the inner coil and up the other suspension wire), the suspended coil will turn and strive to cause a parallelism of the planes and currents of both coils. The turning force of the currents is resisted by an increasing force exerted by the twisted wire suspension. With a certain current the coil will be deflected a certain amount—*i.e.*, until the two opposing forces are equal.

Fig. 382.



With a stronger current the deflection will be greater. Thus the magnitude of the deflection can serve as a measure of the current strength.

A peculiarity of the electro-dynamometer is that it serves to measure alternating currents, *i.e.*, those which change their direction, perhaps, several thousand times per minute, equally as well as continuous currents. A change in the direction of flow of the main circuit changes the direction in *both* coils. This does not alter the direction of the deflection.

CHAPTER VIII.

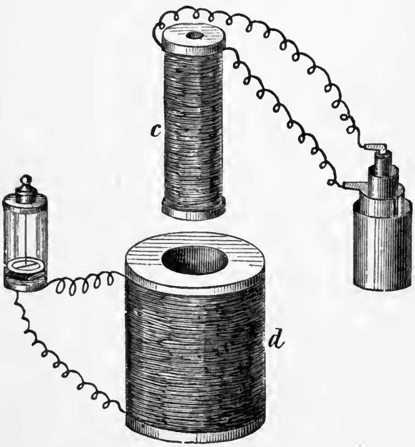
ELECTRO-MAGNETIC INDUCTION.

665. Currents of Electricity Produced by Induction.—It has been shown that when a current of electricity flows through a conductor the air or other dielectric which surrounds the conductor is traversed by lines of force. The presence of these lines indicates that the dielectric is under some sort of a strain. To produce this strain energy must have been expended by the current when it commenced to flow. During the short time that the strain is being produced there is an opposition to the exciting current, which is equivalent to a current in an opposite direction. Now, it is reasonable to suppose that, if lines of force or a magnetic field be produced by some agency around a closed circuit which is primarily traversed by no current, a current will be produced in this circuit. The direction will be opposite to that which would be necessary to create the field, and will last only for the time necessary to produce the strain. Furthermore, upon destroying the field it is reasonable to suppose that the energy which it represents will appear as a current in the same direction as one which could produce the field. These suppositions are substantiated by experiment, as was first shown by Faraday. The currents are called *induced currents* (not to be confounded with induced electrostatic charges), and those currents whose directions are the same as a current which could produce the field are termed *direct currents*, while those in an opposite direction are called *inverse* currents.

666. Methods of Producing the Inducing Field.—Inasmuch as induced currents are produced by any variation in the strength of the field around the conductor which carries them, they can be produced either by varying the strength of the field

current or by moving the conductor into fields of various strengths. For the sake of clearness suppose that we are supplied with the apparatus represented in Fig. 383. c is the *primary coil* of wire which produces the field, and is traversed by a current from the battery. The *secondary coil*, in which induced currents are to be produced, is represented at d. Its terminals are connected with a galvanometer, which indicates the presence and direction of the induced currents. Now suppose that c be placed inside of d. Upon starting the current in c an inverse current will be induced in d, and upon stopping it a direct current will be induced. Permitting the current in c to flow, increasing or decreasing its strength will produce inverse or direct induced currents respectively. If the current strength in c be maintained constant, removing the coil c will produce a direct current, and replacing it an inverse induced current.

FIG. 383.



Induced currents may also be produced by magnets. Consider a magnet to be the equivalent of a solenoid traversed by a current (Art. 651). Dispensing with the battery we have the apparatus indicated in Fig. 384. An inverse current will be induced by the introduction of the magnet into the secondary coil, and a direct cur-

FIG. 384.

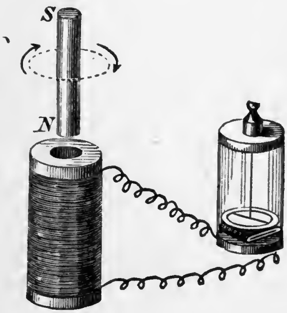
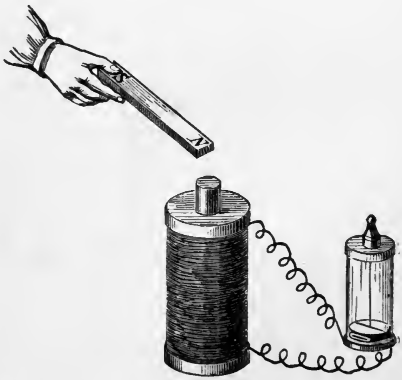


FIG. 385.



rent upon removing it. An inverse current may also be induced by strengthening the field of a magnet which is stationary within the secondary, by bringing a piece of iron near to it. In this case the iron becomes a magnet by induction, as shown in Fig. 385, and adds its lines of force to the field. Direct induced currents will follow the removal of the iron.

It is well to remark that, as motion is merely relative, it is immaterial whether a magnet be placed in a secondary coil or the latter be placed around the magnet.

The facts which have been mentioned may be summed up in a single law:

Inverse induced currents always result from an Increase in the number of lines of force which pass through the circuit, and Direct induced currents always result from a Decrease in the number of these lines.

667. Lenz's Law.—*If two conductors, A and B, in one of which, A, a current is flowing, be made to change their relative positions, then a current will be induced in B in a direction which will cause a mutual action in the two conductors tending to oppose their motion.* Thus, if *A* and *B* be brought nearer together an inverse current will flow in *B*, and currents flowing in opposite directions repel each other; and if *A* and *B* be caused to move apart, then a direct secondary current will flow in *B*, and currents flowing in the same directions will attract each other. This statement of the results of experiments will aid the memory in regard to the directions of the primary or secondary currents.

668. Self-Induction.—Whenever a current is started in a coil of wire, lines of force are created which increase in number from zero to a maximum. Owing to the increase, they induce currents in the coil which are opposite to the direction of the original current. Upon stopping the original current the lines of force decrease in number and thus induce a direct current in the coil. The induction in such a case is termed *self-induction*, and the currents are termed *extra* or *self-induced* currents.

The existence of self-induced currents may be demonstrated by the Wheatstone bridge combination (Art. 646). Let three of the arms of the bridge be made up of resistances without self-induction (Art. 645), the fourth arm consisting of an ordinary unifilar coil. For the purpose of increasing the self-induction of this fourth arm, insert a piece of soft iron in the coil. Obtain a balance in the bridge by employing a constant current. When a balance has been obtained the galvanometer will show no deflection. If the

current be now stopped, the current induced in the fourth arm will cause a deflection of the galvanometer needle.

669. Coefficients of Mutual and Self-Induction.—It can be proved mathematically that the *electro-motive force induced in a closed circuit is equal to the rate of variation of the number of lines of force which pass through it.*

If in a short interval of time dt, the number of lines of force N increases a small amount dN, then the electro-motive force

$$E = -\frac{dN}{dt}$$

will be induced in the circuit which surrounds these lines. In case two coils, a primary and secondary, be fixed in position, and the strength of the current in the primary be increased by an amount dc in the short time dt, then the electro-motive force

$$E = -M\frac{dc}{dt}$$

will be induced in the secondary during that time. M is a constant which is called the *coefficient of mutual induction* between the two coils. Its value depends upon the shape and number of windings of wire around the respective coils and their relative positions. It is numerically equal to the number of absolute lines of force which would be sent through either coil when an absolute unit current of electricity was sent through the other coil. It makes no difference which coil be chosen as a primary in determining M.

If it be supposed that the two coils be made to coincide, *i.e.*, that there be but one coil, then the electro-motive force of self-induction

$$E = -L\frac{dc}{dt}.$$

The constant L is called the *coefficient of self-induction*, and is equal to the number of absolute lines of force which a coil would send through itself if it were traversed by an absolute unit of current.

670. Induced Currents from the Earth.—If a coil (whose terminals are connected with a sensitive galvanometer) be placed so that its axis is parallel with the axis of a dipping-needle (Art. 621), it will be pierced by a maximum number of the earth's lines of magnetic force. If it be now turned through 90° around an axis perpendicular to its own axis, the number of the lines piercing it will decrease to zero, and the galvanometer will indicate that a current is being induced by the rotation.

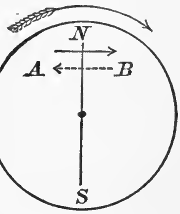
Continuous variations in the strength of the earth's magnetism sometimes induce currents of considerable strengths in long telegraphic circuits. Such currents are known as *earth currents.*

671. Arago's Rotations.—In 1824 Arago observed that the oscillations of a magnetic needle were reduced in number by suspending a copper plate above it. This observed phenomenon soon led him to the discovery that if a horizontal copper disc be made to rotate rapidly, a magnetic needle suspended above it would rotate also. This effect may also be produced with other metals though in less degree.

If a disc of copper be set spinning on an axis, between the poles of a powerful electro-magnet whose circuit is broken, the axis of the disc being parallel to the lines of force, the rotation continues with slight loss of velocity for a long time; but if the circuit be suddenly closed the rotation is at once checked, or possibly stopped. If such a disc be kept in rapid rotation by a suitable band and pulley, after the circuit is closed, the disc will be heated by the action of the magnet.

These effects were explained by Faraday as being due to currents induced in the mass of metal. Thus let a needle, *N S* (Fig. 386), be suspended above a metal disc *A B*. The magnetic currents flow around the needle as indicated in the figure, the currents below the needle from right to left as shown by the dotted arrow, and those above from left to right, as shown by the full arrow. Now suppose the disc to be rotated in the direction from *A* to *B*; the portions of the currents around *N S* which are nearest to the disc will induce in that part of the disc towards *A* currents whose directions are such as to resist the motion of the disc, according to Lenz's law (Art. 667), that is to say, currents will flow in the disc from left to right; while in that part of the disc towards *B*, which is moving away from *N*, the induced currents are from right to left, and so resist the motion of *B away* from *N*.

Fig. 386.

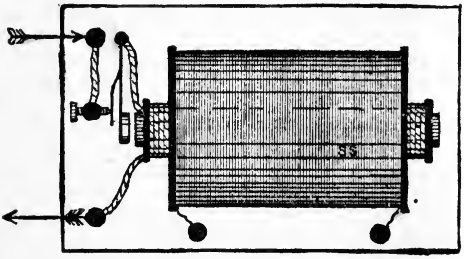


If the needle had been moved, the disc remaining fixed, the same analysis of the motion might be made, and we should find that the disc would resist the motion of the needle. A copper collar or frame is sometimes used to coil the galvanometer wire upon, in order to reduce or *damp* the oscillations of the needle, and bring it more quickly to rest.

672. Induction Coils.—These instruments serve to transform currents of low E. M. F. into alternating currents of high E. M. F. Their forms and sizes are many, and only their principle need be mentioned here. A continuous current of low E. M. F. is passed through a primary coil made of a few turns of coarse insu-

lated copper wire (Fig. 387). The centre of the coil is filled with a core of soft iron wires. Before passing through the coil the current traverses some sort of a current-breaker, *e.g.*, the one shown in the cut acts upon the same principle as the breaker of the electric bell described in Art. 658. By means of this breaker the current in the primary is rapidly made and broken. Alternating currents are thus induced in a secondary surrounding coil, which is wound with many turns of very fine insulated wire. The E. M. F. of these induced currents is great because the coefficient of mutual induction is great. This is owing to the large number of turns of wire in the secondary and to the presence of the iron core. Both conspire to cause a large number of lines of force to pierce the circuit during the short interval required to make the circuit of the primary.

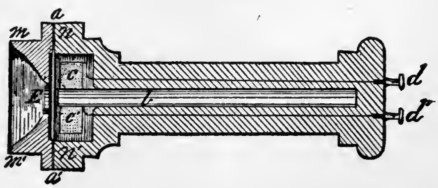
FIG. 387.



The function of the induction coil, as here given, is often reversed, in which case it becomes what is termed a *transformer*. Transformers are much used in the commercial distribution of rapidly alternating currents for lighting and other purposes. Alternating currents of high E. M. F. and low current strength are received from a main line into the finer wire coil of an induction coil. The thick wire coil of the transformer is connected with the customer's home circuit, and delivers to it currents of great strength but at low potential.

673. The Telephone.—This instrument for reproduction of sound at a distance by means of electric currents is shown in section in Fig. 388, in which $a\ a'$ is a disc or diaphragm of thin soft iron, the circumference of which is firmly clamped between the mouth guard $m\ m'$ and the case $n\ n'$, upon the centre of which the sound-waves from the mouth impinge, as at E, and communicate to it vibrations corresponding to the simple or composite sounds uttered. These vibrations of the disc cause a continual variation in the distance of the disc from

FIG. 388.

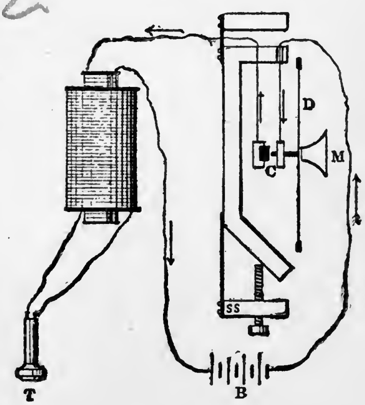


the end of a bar magnet, *b*. Around the end of the magnet nearest to the diaphragm *a a′* is a coil, *c c′*, of fine insulated copper wire, the ends of which are connected with binding-posts, *d d′*. From these posts are carried wires to another precisely similar instrument at the station with which communication is to be held. When a word is spoken into the instrument at *E*, the vibrations communicated to the disc *a a′* cause variations in the magnetic field of the bar *b*, and these variations induce electric currents which flow in the coil *c c′*, and thence through the connecting wires to the coil in the instrument held to the ear of the listener, and these currents in the last-named coil produce variations in the strength of the magnet of the receiving instrument, causing precisely the same vibrations in its diaphragm as were originally set up in the first. The vibrations of the diaphragm are transmitted through the air to the ear; and though no *sound* has been transmitted from one station to the other, the words spoken into one instrument are distinctly delivered by the other. The sound vibrations are the cause of electric currents, and these in turn finally produce sound vibrations again.

To such perfection of action have these instruments been brought, that not only can the spoken words be heard, but the peculiar characteristics of voice are so faithfully reproduced that by these the speaker may be recognized.

674. The Blake Transmitter.—The electro-motive forces generated by the moving diaphragm of the Bell telephone are not sufficiently large to produce satisfactory results on long lines. Therefore an instrument termed a *transmitter* is substituted for the telephone at the sending end of the line. A common and very satisfactory form of transmitter is one designed by Francis Blake. It is represented in Fig. 389, and its action depends upon the principle that the electrical resistance offered by a carbon contact varies greatly with the pressure exerted upon it.

Fig. 389.



The sound to be transmitted is received in the mouth-piece *M*, which causes it to set the diaphragm *D* into corresponding vibrations. Touching the rear of the diaphragm is a platinum or carbon point, which is attached to a piece of watch-spring, and which

is in connection with one terminal of a battery, *B*. (This battery is brought into circuit only as the transmitter is to be used.) The point forms a loose contact, *C*, with a carbon button, which is also mounted upon a spring. The current from the battery flows through this contact to the rest of the circuit. As the diaphragm vibrates it causes the point to exert correspondingly different pressures upon the button. The resistance of the circuit is thus varied, and this results in variations in the current which are the electrical counterparts of the sound vibrations.

A Bell receiver, placed in the same circuit with the battery and transmitter, will yield, besides the transmitted sound, a disagreeable "sizzling" noise. To obviate this an induction coil, *I*, is introduced. The varying current from the battery and transmitter is passed through the primary of a small induction coil, and the line wires, with their receivers included, are connected with the secondary coil. In this case the currents on the line flow in opposite directions to what they would, if connected directly with the transmitter circuit. This, however, is of no consequence.

The springs of the transmitter, which bear the carbon button and platinum point, are fastened to one piece of brass, but are insulated from each other. The amount of pressure at the contact is regulated by a screw, whose end hits the bent end of the brass holder. The holder is supported by pliable spring bands which are attached to the case of the transmitter. Although this method of adjustment is simple and appears crude, the delicacy of it is marvellous.

675. Dynamos.—These machines are for converting mechanical energy into electrical currents. A discussion of the principles of their construction is here out of place, and the student is referred to some one of the many technical treatises on the subject. The principle of their action may be described.

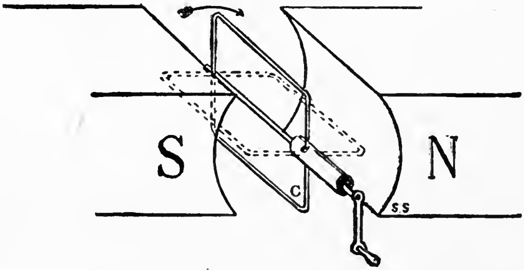
The dynamo has two essential parts—a movable* conductor, called an *armature*, and a magnet, in whose field the armature moves. The armature, by its motion, varies the number of the field lines which pass through it, and is therefore traversed by induced currents.

Fig. 390 (taken from S. P. Thompson's "Dynamo-Electric Machinery") represents an ideal dynamo in its simplest form. *N* and *S* are the poles of a field electro-magnet. The lines of force pass between the poles and pierce the looped conductor *C*, which forms the armature. The armature, in the position indicated by the con-

* In some machines the armature is stationary and the field magnets are movable.

tinuous lines, is pierced by a maximum number of the field lines; upon turning through 90°, coming then into the position indicated

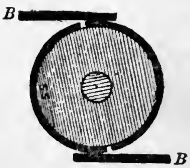
FIG. 390.



by the dotted lines, it is pierced by none of the lines. During the whole quarter revolution there has been a decrease in the number of lines passing through the loop. An induced current, flowing in a certain direction, has accompanied the movement. During another quarter revolution the number of penetrating lines will be on the increase, but they now pass through the loop in an opposite direction to what they did before, and hence the induced currents which result from the increase are in the *same direction*, referred to the conductor, as during the first quarter revolution. During the next two quarter revolutions the induced currents will flow in an opposite direction. Thus by continuous revolution the armature is traversed by currents which reverse their directions twice each revolution.

In order to lead the currents from the armature into a circuit where they can be used, and in order to rectify them, *i.e.*, cause them to flow in the same direction, use is made of a *commutator*. Fig. 391 represents a two-part commutator suited for our single-loop armature. It consists in an insulating cylinder, to be applied to the extremity of the axis of the armature. Upon it is slid a metal tube slit into two parts. To each part is connected one of the ends of the loop, as shown in Fig. 390. Against the commutator are pressed two spring *brushes*, *B B*, which are connected with the two terminals of the outside circuit respectively. The commutator revolves with the armature, but the brushes remain stationary. Both are so arranged that at the instant the plane of the loop of the armature passes through the vertical plane, the brushes will slide from one segment of the commutator to the other. At this instant the induced current reverses the direction of its flow, and the commutator, exchanging

FIG. 391.



the connections with the external circuit, causes the external current to flow in one direction.

The E. M. F. which could be obtained from such an ideal dynamo would be very small. To increase it, the total number of lines of force which are passed through or taken out of the circuit in a unit time must be increased. There are three ways in which this may be accomplished: the *speed* of revolution, the *number of loops* in the armature, or the strength of the *field* may be increased. It need not be considered here how this is carried out in practice.

The field magnets of a dynamo may be excited by currents from an external source, by the whole of the machine's armature current, or by only a portion of the armature current. The dynamos are then termed *separately excited*, *series*, or *shunt* machines respectively.

When the field is furnished by permanent magnets the machine is no longer termed a dynamo, but a *magneto-electrical generator*. Such machines are not a commercial success except in the very small sizes.

676. Electric Motors.—The function of these machines is the converse of that of dynamos. They are intended to transform electrical energy into motion. The dynamo of the previous article becomes an ideal motor by simply sending through it, from the external circuit, a current in an opposite direction. The commutator accomplishes that the lines of force, due to the current flowing in the armature, shall never become parallel to the field's lines. In striving to secure such parallelism the armature revolves upon its axis, and just as it is about to reach the goal the commutator reverses the direction of its lines, and it moves through another half revolution to be again frustrated in its attempts.

CHAPTER IX.

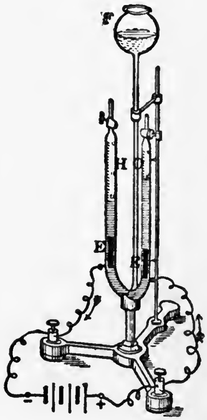
ELECTRO-CHEMISTRY AND ELECTRO-OPTICS.

677. Electrolytes.—Liquids may be divided into three classes, depending upon their behavior towards the electrical current—those which do not conduct at all, as kerosene, turpentine, and oils generally; those which conduct without decomposition, *e.g.*, mercury and molten metals; those which are decomposed when they conduct a current, *e.g.*, solutions of acids or metallic salts and certain fused solid compounds. The liquids of the last class are called *electrolytes*, and the process of decomposing an electrolyte by

means of an electrical current is termed *electrolysis.* The two parts into which the electrolyte is decomposed are termed *ions.*

678. Electrolysis of Sulphuric Acid.—If a current of electricity flows into a solution of sulphuric acid (H_2SO_4) in water by means of an electrode, and if, after traversing the solution, it flows out through another electrode, then it will, by its passage, decompose the acid into two parts—H_2 and SO_4. *The hydrogen will appear,* in the form of gas bubbles, *at the electrode through which the current makes its exit from the solution.* The SO_4 will endeavor to appear at the electrode where the current entered, but the water of the solution seizes upon it, and together they form sulphuric acid, leaving, however, one portion of oxygen to appear, as gas, at the electrode. The effect of the passage of the current is to virtually decompose water (H_2O) into hydrogen and oxygen, there being twice as much of the former as of the latter.

Fig. 392.



Hoffmann's apparatus for electrolyzing sulphuric acid is shown in Fig. 392. The dilute acid solution is poured into the funnel *F*, and flowing into the two arms of the front **U**-tube fills them, providing the stop-cocks at their tops be opened. After filling, the cocks are closed and a current is made to pass between the two platinum electrodes *E E.* The gases which are evolved at the electrodes rise in the respective tubes above them and displace the liquid. These gases are subjected to the same pressure exerted by the liquid in the funnel. Their volumes may be read off from graduations on the tubes containing them. The gases may be taken off through the cocks and their natures tested—the oxygen being made to relight a glowing taper and the hydrogen being made to explode when mixed with air in a test-tube.

679. Metallic Salts.—When the electrolyte is a metallic salt solution *the metal will be deposited at the electrode where the current leaves the solution.* The acid of the salt appears at the other electrode. The metal may be deposited upon the surface of the electrode in the form of a thin metallic film. In case the metal has a strong affinity for the water of solution, *e.g.*, sodium in water, it will go into solution and hydrogen will be evolved as a secondary product. It is nevertheless true that Davy obtained metallic sodium and potassium by the electrolysis of strong caustic soda

and potash. These metals may be obtained by electrolysis, if a mercury electrode be employed. They then appear in the form of amalgams.

The character of a deposited metal often varies under different current strengths or different concentrations of solution. Copper may be deposited in the form of a black powder instead of an even metallic film. Silver may appear in the form of crystals. Platinum generally appears as a black, finely divided sponge. Tin, from tin chloride, forms a beautiful "tree" of tin crystals, the branches spreading out gracefully from the electrode.

680. Faraday's Laws.—Faraday proved that *a given quantity of electricity always deposits the same weight of a given ion* from an electrolyte through which it passes. Thus a coulomb of electricity always deposits .001118 gram of silver on an electrode. It makes no difference whether the electrolyte be molten silver iodide or chloride, or whether it be a water solution of silver nitrate, sulphate, acetate, or cyanide. The passage of one coulomb is always accompanied by the deposition of this much silver. *The weights of other chemical elements which a coulomb will deposit are in proportion to their chemical equivalents* This being so, it must be concluded that a given quantity of electricity ruptures the same number of molecular valencies, whatever the electrolyte may be.

681. Voltameters.—From Faraday's laws it will be readily seen that from weighing the amount of an ion, which is deposited by the passage of a certain quantity of electricity, this quantity may be determined. Thus, if a certain quantity deposits silver on an electrode so as to cause it to weigh 1.118 gram more than before the passage, it is evident that 1,000 coulombs have passed. If the quantity passed in the form of a *constant* current, which lasted for 1 second, then the current strength was 1,000 amperes. For an ampere means a strength of current which delivers 1 coulomb per second, but in this case 1,000 coulombs were delivered in a second. In general, if $z =$ the electro-chemical equivalent of the substance deposited, *i.e.*, grams per coulomb, $c =$ the current in amperes, $t =$ time in seconds that the current was maintained, the weight of the substance deposited

$$w = c\, z\, t.$$

In case w and t are measured, the current strength may be determined by the formula

$$c = \frac{w}{z\, t}.$$

Instruments for measuring current strengths in this manner are called *voltameters*. The substances generally employed for depo-

sition are copper from a solution of its sulphate, silver from its nitrate, and hydrogen from dilute H_2SO_4. In the case of hydrogen weighing is difficult, hence the volume is measured and then reduced to 760 mm. pressure and 0° C.

A current of 1 ampere deposits in 1 minute, of

Hydrogen (at 760 mm. and 0° C.)	6.942 cu. cm.
Copper	.01969 gram.
Silver	.06708 gram.
Zinc	.02018 gram.

The Edison electrical companies place zinc voltameters in the houses of their customers, and thus measure the quantity of electricity consumed.

682. Theory of Electrolysis.—The most satisfactory explanation of the phenomena of electrolysis is embodied in the theory of Grotthuss, somewhat modified by Clausius. The molecules of an ordinary solution are supposed to be in constant vibration in all possible directions. Owing to collisions between the molecules, or other causes, the constituent atoms are constantly leaving their partners and combining with others to form new molecules. Every molecule, having unit valency, is charged with the same quantity of electricity—half being positive and half negative. The positive resides on one ion of the molecule and the negative on the other. Now, upon subjecting the solution to a difference of potential between the electrodes, the *direction* of the molecular motions is controlled, and ions, which by chance are isolated, will tend to move towards one or the other electrode, according to the signs of the charges which are upon them. If the impressed electromotive force is large enough to prevent recombination of these ions, they will continue their movements towards the electrodes, and will accumulate around them. Upon touching the electrodes they impart to them their minute charges and the continuous accumulation of these maintains a current in the circuit.

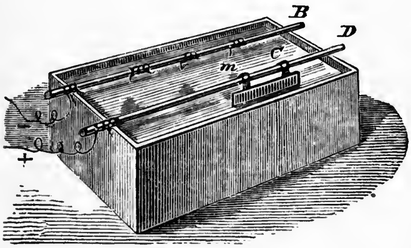
According to this theory, electrolytic conduction of electricity is similar to the convection of heat in liquids. The transportation of electricity is accompanied by a transportation of matter.

The remarkable connection between the results of the quantitative work of Faraday and the chemical equivalents of the elements, points to electrolysis as a fertile field for the investigation of the yet unknown nature of chemical affinity.

683. Electroplating.—The principles of electrolysis are made use of in the mechanic arts. Articles made of baser metals are covered over with a thin deposit of silver or gold and are said to

have been *electroplated.* The articles to be plated are suspended in a *bath* from a metallic rod, which is in electrical communication with the negative pole of a battery or dynamo (Fig. 393). The bath consists of a solution of some salt of the metal which is to be deposited, *e.g.*, silver or gold cyanide. The current from the positive pole of the dynamo enters the solution by means of an electrode, *C*, made of the same metal as that which is contained in the salt. Upon passing a current, the salt of the solution is decomposed—the metal depositing on the article to be plated, and the acid combining with the electrode *C* to form new salt, thus maintaining the concentration of the solution. The articles to be plated must be thoroughly scoured and cleansed before immersion in the bath. The character of the results obtained depends much upon the character and concentration of the baths and upon the magnitude of the currents and electro-motive forces employed. Full details must be looked for in technical books.

FIG. 393.



684. Electrotyping.—If the object to be plated consists of an impression, in wax or paper pulp, of the *type* from which a page is printed, the impression having been coated with fine plumbago to render it a good conductor, copper deposited upon it may be removed, and having been stiffened by melted lead (or some alloy) poured over its under surface, it may be used in the printing-press instead of the type. It is then called an *electrotype plate,* and when not in use may be preserved indefinitely for succeeding editions, while the type of which it is a copy can be distributed and used for other purposes.

685. Counter-Electromotive Force.—If a current be sent through a solution of alkaline zincate by means of two copper electrodes, zinc will be deposited on one electrode and the other will become oxidized. If the connections with the source of electricity be now removed and transferred to an electric bell, the bell will ring. The bath and electrodes have been transformed into a galvanic cell. The current which it gives is in a direction opposite to that which caused the decomposition of the solution. Its E. M. F. is about 0 79 volt, and is opposed to the original E. M. F. Had the original E. M. F. been less than this amount, no plating of the

electrodes could have occurred. The E. M. F. developed in the solution is termed a *counter-electromotive force.* It occurs in nearly all electrolytic actions, except when the electrodes are of the same metal as that which is being deposited, *e.g.*, copper in copper sulphate.

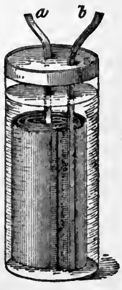
The counter-electromotive force developed in the electrolysis of dilute sulphuric acid is about 1.47 volt. Hence, to perform the electrolysis, more than one Daniell's cell is necessary.

The counter-electromotive force constitutes the polarization of a primary battery mentioned in Art. 634.

686. Storage Batteries.—The copper electrodes in alkaline zincate of the preceding article represent a very simple form of *storage battery* or *electrical accumulator.* Upon sending a current through it, the zinc is deposited and the battery is said to be *charged.* Some of the electrical energy has been transformed into chemical energy. The electrodes may be removed from the solution, packed away, and then be brought forward in the future and be made to turn back their energy into electricity. The electricity proper has not been stored away, but the energy represented by it.

The first successful storage battery was constructed by Gaston Plantè in 1860. His electrodes were made of sheet-lead, and the electrolyte was dilute sulphuric acid. In order to expose a large surface of electrodes he made them of large sheets which he coiled up into spirals, as shown in Fig. 394, the two plates being insulated from each other by rubber bands between the spirals. The object of the large surface was to increase the capacity of the cell. The spiral form was conducive to a small internal resistance. Upon the passage of a current the acid was decomposed and hydrogen reduced one electrode to bright metallic lead, while oxygen coated the other with peroxide of lead. These two conditions of the electrodes rendered them capable of giving an electro-motive force of two volts. By repeated charging in alternate directions the surfaces of both electrodes were rendered spongy, thus exposing an increased surface to the action of the ions and increasing the capacity of the cell accordingly. This preliminary alternate charging was termed by him "formation" of the electrodes, and was performed at the expense of costly currents.

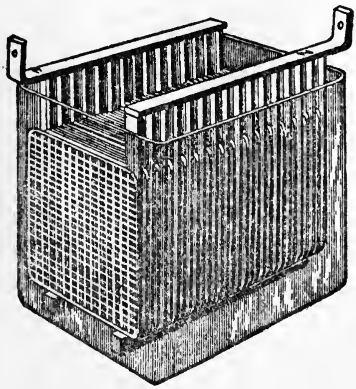
Fig. 394.



In order to reduce the time and expense of formation, Faure used lead plates as a support and covered them with a paste made of powdered oxide of lead mixed with sulphuric acid. This paste he kept in place by covering the sheets with felt. When the

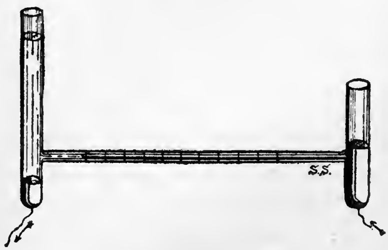
charging current was connected the oxide on one plate was changed to a higher oxide, and on the other plate transformed into metallic sponge. This idea of Faure was an excellent one, and is at the foundation of the construction of all the commercial lead accumulators. The percentage of energy recovered by discharge was greatly increased. His method of keeping the paste in place by felts was, however, soon abandoned, because fine lead needles soon filled up the interstices of the felt, and thus made a metallic connection between the electrodes. Holes were then punched in the lead plates and the paste pressed into them. A large number of the patents recently issued for accumulators refer to methods of making these holes and pressing in the paste, or to the shape of the holes themselves after they have been punched. The shapes vary from a slight depression on the surface to a hole completely through the plate, and even further, to a hollow plate, with small openings leading to the surface. A great deal depends upon this shape, for the paste changes its volume during the process of charging and discharging, and it would tend to loosen itself from some shaped openings and fall to the bottom of the cell, while in others it would tend to tighten itself, and thus provide a better contact.

FIG. 395.



A modern commercial storage battery is shown in Fig. 395. The electrodes are made up of a number of pasted plates, or *grids* as they are called. The grids of one electrode are alternated with those of the other, and are all connected by *lugs* with common cross-bars which constitute the terminals of cell.

FIG. 396.



687. Capillary Electrometer.—This instrument is for the measurement of small differences of potential not exceeding 1 volt. A simple form is represented in Fig. 396. It consists of two upright test-tubes connected by a horizontal capillary glass tube of about $\frac{1}{2}$ mm. internal diameter.

Into one of the test-tubes is poured mercury and into the other dilute sulphuric acid. The heights of the two liquids are so arranged that the dividing surface between them shall be in the horizontal tube. Upon subjecting the two liquids to an electro-motive force, applied at two platinum terminals fused into the bottoms of the test-tubes, an electrolytic action will be started at the point of the capillary tube where the acid meets the mercury. The surface tension will be accordingly modified and the balance between the two columns will be destroyed. To reproduce a balance the dividing surface must move along the capillary tube in one direction or the other, depending upon which liquid has the higher potential. The distance moved depends upon the potential difference and becomes a measure of it.

688. Light and Electricity.—At the present time many investigators are experimenting upon the close relation between the phenomena of light and those of electricity. Trustworthy results point to the fact that electricity is the luminiferous ether itself, as was previously stated. A motion of the ether is unrestrained in a perfect electrical conductor. In a dielectric only a limited displacement of the ether particles is possible, except in case the dielectric is ruptured. A displacement always subjects the enclosing dielectric to a strain, and can be produced by a neighboring conductor having an electrostatic charge or by its conveying an electrical current. The displacement resulting from a current is in a direction opposite to the current, and occurs through all the dielectric which surrounds the current. Upon starting the current the displacements near the conductor occur before those at a distance. The velocity of propagation of the first impulse causing displacement is the same as the velocity of light.

A full exposition of the ether hypothesis, and to what extent it explains electrical phenomena is, of course, out of place here.

689. Double Refraction from Electrostatic Strain.—Kerr showed that the strain in a dielectric, caused by electrostatic difference of potential, could be detected by means of polarized light. He placed a block of glass between two Nicol's prisms which served as analyzer and polarizer. Into opposite sides of the glass were bored two holes, not quite meeting each other, but separated by about 2 mm. Into these holes were placed wires, which were connected with the poles of a Holtz machine. Upon creating a difference of potential between the ends of the wires the glass was subjected to strain and exhibited to an eye placed at the analyzing Nicol similar colors to those given by mechanically strained glass. The glass was made doubly refracting.

690. Magneto-Optic Twisting of the Plane of Polarized Light.—Faraday discovered that the plane of polarization of a ray of light which traversed a magnetic field in a direction parallel to the lines of force was twisted by the field. One form of Faraday's experiment is to place a straight electro-magnet between two Nicol's prisms, which have been crossed so as to produce extinction of light. Substitute for the iron core of the magnet a tube with glass ends, which is filled with bisulphide of carbon. Before the magnet is excited a ray of light from the polarizer passes through the liquid and is brought to extinction by the analyzer. If, now, the magnet be excited by an electrical current, the analyzer no longer extinguishes the ray, and that it may do so must be rotated through a certain angle. The plane of the ray has been twisted or rotated by the magnetic field. The direction of the rotation is the same as the direction of the exciting current. By reversing the current the plane will be twisted in an opposite direction. The amount of the rotation of the analyzer necessary to reproduce extinction of the ray is directly proportional to the length of the tube and to the strength of the magnetic field, *i.e.*, to the strength of the exciting current. It also depends upon the nature of the liquid in the tube. In general it may be said that substances of high refractive indices have large rotatory powers.

As might be expected, rays of the different colors are rotated through different angles. Hence, if complete extinction by large rotations be desired, monochromatic light should be used.

691. Rotation of the Plane by Reflection.—Kerr discovered that the plane of polarization was rotated when the ray was reflected from the polished pole of the iron core of an electro-magnet. In this case the direction of rotation was contrary to the direction of the magnetizing currents.

692. Photo-Electric Properties of Selenium.—Selenium, when thoroughly annealed, offers a resistance to an electric current which is dependent upon the degree to which it is illuminated. An increase of illumination decreases the resistance. A piece of selenium, whose resistance in the dark was 500 ohms, has been known to decrease its resistance to 50 ohms upon exposure to bright sunlight.

This peculiarity of selenium is made use of by Bell in the construction of his *photophone.* This instrument is intended for transmitting sounds to a distance by means of rays of light, which are reflected from a mirror that is made to vibrate by the sounds. Light of varying intensity is made thus to impinge upon a piece of selenium, which is connected in circuit with a battery and a Bell

telephone receiver. The variations in the resistance of the selenium, because of the varied illumination, cause variations of the current in the receiver, which serve to reproduce the sounds.

Quite recently Shelford-Bidwell has exhibited an apparatus in which selenium is made to light the gas as darkness comes on and to turn it off as daylight appears.

Problems.

1. How much copper will be deposited by a current of 3 amperes in an hour?

2. A current of 0.5 ampere is used for preparing pure silver by electrolysis: how long must the current be allowed to flow in order to obtain a deposit of 4 grams?

3. What is the strength of a current which deposits a milligram of copper per minute?

4. It is found that a current of 1.868 ampere deposits 1.108 gram of copper in half an hour: what value does this give for the electro-chemical equivalent of copper?

5. What is the strength of a current which deposits 0.935 gram of copper in 1 hour and 10 minutes.

CHAPTER X.

THE RELATIONS BETWEEN ELECTRICITY AND HEAT.

693. Power of the Electrical Current.—A current whose strength is c carries in t seconds $c\,t$ units of electricity from a potential V to one of V'. The work which has to be expended in doing this is $c\,t\,(V' - V)$, as was shown in Art. 567. In this case $V' - V$ is equal to the electro-motive force E, which is sending the current. Hence, representing the work by A, we have

$$A = c\,t\,E.$$

If c, t, and E are measured in absolute units, the work is given in ergs.

The *power* of the current P being the rate at which the work is done, *i.e.*, the work divided by the time required to perform it is expressed by the formula

$$P = \left(\frac{A}{t}\right) = c\,E.$$

Expressing c and E in *amperes* and *volts* respectively will di-

vide the ergs per second by 10^7. This gives the power in *watts* (Art. 38).

Inasmuch as $c = \frac{E}{R}$ and $E = c\ R$, by Ohm's law, these values may be substituted, and we have, further,

$$P = \frac{E^2}{R} \text{ and}$$
$$P = c^2\ R.$$

694. Heat Developed in a Conductor.—Whenever the energy which is represented by a current is not expended in doing external work, as in driving motors or decomposing electrolytes, it is transformed into heat. The conductor which carries the current becomes heated. If a conductor of resistance, R, carries a current c, then, by Ohm's law, the difference of potential between its ends, $E = c\ R$. The energy represented by the current is, as in the preceding article,

$$A = c\ t\ E = c^2\ R\ t \text{ ergs.}$$

This energy is transformed into heat. To express the heat in gram-calories, Joule's mechanical equivalent of heat must be introduced. Without going through with the transformations it is sufficient to say that a current of c amperes flowing for t seconds through R ohms communicates to the conductor carrying it

$$H = c^2\ R\ t\ 0.24 \text{ gram-calories.}$$

695. Rise in Temperature of the Conductor.—A long thick wire could have the same resistance as a short thin one, but a given current traversing them for a given time would produce the same quantities of heat in each. The short thin wire, not weighing so much, might have its temperature raised several hundred degrees, while the thick wire would suffer a rise of a few degrees only.

In order to determine what rise in temperature will accompany a given quantity of heat imparted, account must be taken of the dimensions of the conductor, the specific heat of the substance of which the conductor is composed, and the temperature coefficient of the conductor, *i.e.*, the amount by which its resistance would increase under a rise of one degree of temperature. A full consideration cannot be considered in these chapters. It is well to know, however, that, *in different wires of the same material, traversed by the same current, the rise in temperature is inversely proportional to the fourth power of their diameters.*

A wire of given resistance, traversed by a given constant current, will receive the same amount of heat each second that the current flows. After a short time the temperature of the wire may rise to

such a point that it gives off to surrounding objects, by radiation and conduction, just as much heat as it receives in every second. The temperature then remains constant at this point as long as the flow is maintained.

The heat effects mentioned may be illustrated by sending a strong current through a chain, whose alternate links are made of platinum and silver wire. The platinum links will be heated to luminosity while the appearance of the silver remains unaltered. The reason for this is that the platinum offers a much greater resistance than the silver, and its specific heat is less.

Platinum wires, heated red-hot by currents, are much used by surgeons for cauterization. They are much easier of manipulation than the knife.

696. **Hot Wire Ammeters and Voltmeters.**—The expansion in length which a wire undergoes when its temperature is raised to a certain point by a current which traverses it, can be made a measure of the strength of the current. A given wire has a definite length at a given temperature. Increasing the temperature increases the length. Every current produces a definite length in the wire. Different current strengths correspond to different lengths. A measurement of the length can thus be made a measure of the current strength.

A simple *ammeter*, whose action depends upon this principle, is represented in Fig. 397. The current to be measured is passed

Fig. 397.

through a long and thin platinum or iron wire, one of whose ends is clamped in a stationary binding-post. The other end passes around and is fastened to a small metallic cylinder. This cylinder turns upon a metallic pivot fastened in another binding-post. The current having traversed the wire leaves it by this binding-post. The wire is subjected to a constant strain, exerted by a spiral spring attached to the periphery of a disc, which is fastened to one end of the cylinder. The disc carries a radial pointer, whose end moves over a graduated scale whenever the length of the wire is changed by a change in temperature caused by a current. The

graduation of the scale is empirical, being determined by the assistance of some other current measurer.

As the current strength is dependent upon the difference of potential between the two binding-posts, it is evident that the instrument may be graduated as a *voltmeter, i.e.*, will indicate the volts impressed upon it. As it is not desirable that a large current should flow through a voltmeter, the wire of such an instrument should have a large resistance. The voltmeters of Cardew are constructed on this principle. Sometimes a high resistance coil is inserted in series with the wire, and then the voltmeter readings indicate the fall in potential between the terminals of the spool and wire in series.

Hot wire ammeters and voltmeters can be employed to measure currents and voltages which rapidly alternate their directions. For the heat produced being dependent on the square of the current strength is *positive*, whether the current flows in a positive or negative direction.

697. Electric Welding.—The welding together of two pieces of metal, by means of the electric current, as done in the Thomson process, depends upon the heat produced. The pieces are pressed together and a powerful current (sometimes 50,000 amperes) is sent across the juncture. The consequent heat renders the metal plastic, and upon cooling a most perfect joint is obtained.

FIG. 398.

698. The Electric Arc.—If two rods of carbon, traversed by a current from a source of at least 40 volts electromotive force, be touched together at their ends and then be separated by a few millimeters' distance, an electric flame or arc will be observed to pass over this distance. A brilliant light will accompany it, the extreme brilliancy being at the end surfaces of the rods. If allowed to burn for a few moments the rods and flame will present an appearance like that represented in Fig. 398. The end of the positive rod will have formed itself into a sort of crater, while the end of the negative will have become pointed. If allowed to burn for some time, the rods will be consumed, and, in a

given time, about twice as much of the positive rod will be consumed as of the negative.

In order to form an *arc* it is necessary that the points be at first in contact. When in loose contact the current encounters a great resistance, and accordingly heats the points until a temperature is reached which is sufficient to vaporize the carbon. Carbon vapor is a much better conductor of electricity than air, and whereas an arc could not be maintained across an air space, yet it can be across a space filled with this vapor.

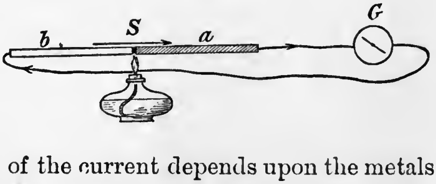
The heat at the vapor portion of the arc is intense, being sufficient to vaporize the most refractory substances, of which carbon itself is the best example. The heat at the crater, though not so intense, is the cause of greater illumination, because of being associated with a solid instead of a vapor.

Recent investigations, concerning the fall of potential along the arc, indicate that a large portion of the electrical energy represented by it is consumed in maintaining the heat of the crater.

699. Incandescent Electric Lamps.—These lamps consist of filaments of carbonized bamboo, paper, or silk, which are heated to incandescence by the current. That the filaments may not be consumed by combustion, they are sealed into glass bulbs, from which the air has been exhausted. Although no oxygen is present, the filaments become disintegrated by continuous use. Particles of carbon escape from the surface of the filament and are oftentimes deposited upon the interior of the bulb, causing a brownish opalescent appearance.

700. Thermo-Electricity.—Let two bars of bismuth (b) and antimony (a) be soldered together as in Fig. 399. If, now, the joint S be heated by a lamp a current will flow across the heated junction from the bismuth to the antimony, as will be shown by the galvanometer G.

Fig. 399.



The electro-motive force of the current depends upon the metals in contact at the heated junction. If any one of the metals given below be joined with any one following it in the list, upon applying heat the current will flow across the junction from the former to the latter: Bismuth, lead, platinum, tin, zinc, copper, iron, antimony.

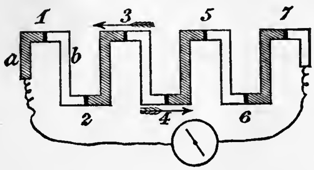
The thermo-electro-motive force is proportional to the difference of temperature between the junction and the rest of the circuit.

The E. M. F. of a single thermo-element is very small. If the junction of a copper-iron element be heated 1° C. above the temperature of the rest of the circuit, the E. M. F. developed is about fourteen millionths of a volt.

In some cases, *e.g.*, with iron, a continued increase of temperature at the junction finally reverses the direction of the current.

701. Thermo-Electric Pile.—If a series of bars of bismuth and antimony be arranged, as in Fig. 400, and the junctions marked 3 and 4 be equally heated, no current will be indicated by the galvanometer; for the flow at 3 would be from the bismuth to the antimony as indicated by the arrow, while at 4 it would also be from *b* to *a*, as shown, and these two currents would neutralize each other. But if we heat only one set of junctions, the odd-numbered for instance, then a current flows whose electro-motive force is proportional to the number of heated junctions.

Fig. 400.



A set of twenty or thirty pairs, conveniently arranged so that the alternate junctions may be simultaneously subjected to heating or cooling effects, is called a *thermo-pile,* and has been an important instrument in investigations upon radiant heat.

702. Peltier Effect.—Peltier discovered a phenomenon which is the converse of that mentioned in the preceding articles. He found that, if a current of electricity be sent through a junction of dissimilar metals, the junction becomes heated or *cooled* according to the direction of the current. For instance, if a current be sent through a junction from bismuth to antimony, the junction will absorb heat, *i.e.*, become cooled. If the current be reversed the junction will become heated.

The heat thus produced is not owing to the resistance of the conductors. For the heat from resistance is not altered by a change in the direction of the flow of the current. Cooling can never result from ohmic resistance. Again, the heat of the Peltier effect is proportional to the current strength simply, whereas the heat from resistance is proportional to the square of the current strength.

Problems.

1. An 11,000 watt dynamo develops an E. M. F. of 110 volts: (*a*) What is the current strength in the mains? (*b*) How many incandescent lamps, of 220 ohms hot resistance, will it light, provid-

ing they are arranged in multiple arc? (*c*) How many gram-calories will be developed in each lamp per second? (*d*) How many watts will be consumed by each lamp?

Ans. (*a*) 100 amperes.
(*b*) 200 lamps.
(*c*) 13.2 calories.
(*d*) 55 watts.

2. How much power is required to properly operate an arc lamp which carries 10 amperes and has a difference of potential of 45.2 volts between its terminals?

3. How many calories are developed per minute in a wire of 100 ohms resistance, traversed by 5 amperes?

4. A wire of 2 ohms resistance placed in 100 grams of water is traversed by a certain current, which, in 20 minutes, raises the temperature of the water from 18° to 28° C.: what is the current strength? *Ans.* 1.32 amperes, nearly.

The Electrical Units.

Electrical magnitudes may be expressed in three different sets of units. Two of them—the *absolute electrostatic* and the *absolute electro-magnetic* units—are termed absolute because they are units derived from the absolute units (Art. 4) of length, mass, and time, viz., the centimetre, gram, and second. The third set are called *practical* units, because they are the ones which are employed by practical electricians. They are either decimal multiples or decimal parts of the electro-magnetic units.

Electrostatic Units.

The Unit of Quantity of electricity is that quantity which, when placed at a distance of one centimetre from a similar and equal quantity, repels it with a force of one dyne (Art. 563).

The Unit Strength of Current flows in a circuit when a unit quantity of electricity passes any section of the conductor in one second.

The Unit Difference of Potential exists between two points when it requires an expenditure of one erg of work to bring a unit quantity of electricity from one point to the other against the electric force.

The Unit of Resistance is offered by that conductor which, when interposed between two bodies whose potentials are maintained at a constant difference of unity, allows a unit current to pass along it.

The Unit of Capacity is possessed by that conductor which requires that it be charged with a unit quantity of electricity in order that its potential may be raised from zero to unity.

Electro-magnetic Units.

The Unit Strength of Current is such that, when flowing through

a conductor of one centimetre length which is bent into an arc of one centimetre radius, it will exert a force of one dyne on a unit magnetic pole situated at the centre.

The Unit Quantity of electricity passes in one second through a section of a conductor which is traversed by a current of unit strength.

The Unit Difference of Potential (*or of Electro-motive Force*) exists between two points when it requires the expenditure of one erg of work to bring a unit of electricity from one point to the other against the electric force.

The Unit of Resistance is offered by that conductor which. when interposed between two bodies whose potentials are maintained at a constant difference of unity, allows a unit current to pass along it.

The Unit of Capacity is possessed by that conductor which requires that it be charged with a unit quantity of electricity in order that its potential may be raised from zero to unity.

A little consideration will show that in the electrostatic and electro-magnetic systems the definitions of all the units except that for quantity are identical. Whereas the electrostatic unit of quantity is determined from its exerting a dyne of force on another unit quantity, the electro-magnetic unit of quantity is determined from its exerting a dyne of force, when moving as a current, on a unit magnetic pole. The electro-magnetic unit is about 3×10^{10} times the electrostatic unit. This numerical factor is the same as the velocity of the propagation of light expressed in centimetres per second. This fact, combined with certain mathematical relations which exist between the two units, is of great significance in sustaining the ether theory of electricity.

Practical Units.

Many of the absolute units would be inconveniently large and others would be inconveniently small for practical use. Therefore the following units, based upon the electro-magnetic units, are used:

Electromotive force	*Volt*	$= 10^8$	electro-magnetic units.
Resistance	*Ohm*	$= 10^9$	" "
Current.................	*Ampere*	$= 10^{-1}$	" "
Quantity...............	*Coulomb*	$= 10^{-1}$	" "
Capacity...............	*Farad*	$= 10^{-9}$	" "

Even these units are not of a magnitude suited for the use of all electricians. Thus a physician uses currents whose strengths can be more easily expressed in thousandths of an ampere. The prefix *milli-* is therefore used for "one thousandth" and a *milliampere* is the thousandth part of one ampere. Capacities are best expressed in millionths of a farad or *microfarads*. The high resistances offered by insulations are conveniently expressed in *megohms* = one million ohms.

A COURSE IN ELECTRICAL MEASUREMENTS.

INTRODUCTORY.

To the Instructor.—The student who carries out the experiments outlined in the following course will become acquainted with methods generally employed in determining electrical magnitudes. The accuracy of the results which he may obtain is largely limited by the care exercised in eliminating disturbing conditions, and to a certain extent by the character of the apparatus employed. It is possible, however, to make very accurate measurements with quite ordinary apparatus. A laboratory should possess a standard resistance coil, a standard thermometer, and a set of standard weights. A cheap rheostat, if wound with wire of negligable or known temperature coefficient and of small thermo-electric power (*e.g.*, manganin), can be calibrated with the aid of the standard resistance and be made to yield accurate results. Standard Weston voltmeters and ammeters are great conveniences. The cheap D'Arsonval galvanometers sold by Queen & Co. may, however, be used both as ammeters and as voltmeters. Observations should be made by means of a telescope and scale. Telescopes which are entirely satisfactory may be made from ordinary spectacle lenses. If the telescope be kept at a fixed distance from the mirror of the galvanometer, a suitably sized copper wire shunted between the galvanometer terminals will reduce it to a direct-reading ammeter independent of temperature variations, but liable to slow alterations, owing to decrease in strength of the magnets with the time. A high resistance of proper magnitude placed in series with the galvanometer transforms it into a direct-reading voltmeter. High resistances of any magnitude (approximate) may be purchased from the Dixon Crucible Co., of Jersey City, for a few cents. They are of graphite and in form of rods. Their ends can be copper-plated and copper wires can be soldered to the plating. Adjustments can be made by scraping

away a portion of the plating. These galvanometers, if of high resistance (1,000 ohms), may be used for all the work in this course. When used as ballistic galvanometers, the period of oscillation is rather small, and, further, it must be constantly borne in mind that the damping is dependent on the resistance of the circuit. Some of the exercises require that electricity be taken from the electric-lighting street circuit. These exercises are more conveniently carried out in this manner, but may be performed with the assistance of batteries. When the street circuit is of constant potential, the amount of current employed is conveniently regulated by means of altering in number interposed electric lamps, coupled in multiple arc.

To the Student.—Physical laboratory instruction, to be of most value in education, should develop in the student:

1. A habit of observation of the phenomena of nature, both ordinary and extraordinary.
2. The ability to accurately and truthfully record these observations in a note-book.
3. The ability to draw correct and logical inferences from the noted observations, and
4. The ability to present in concise and perfect English the observations and the results to be inferred from them.

In general, it is always advisable to use the greatest possible accuracy of observation that is allowable with the apparatus employed. In some cases, however, when other observations of less possible accuracy are to be combined in forming a final result, less care may be taken. A single observation is no security against blunders. A number of observations is, however, and, in addition, diminishes the probable error of the mean. Errors of observation, and all errors which are as liable to be above as below the true value, can be diminished in this manner only. Instrumental errors can sometimes be obviated by changing in each observation the conditions of the experiment; for example, in measuring the length of an object by means of a scale, an error of the graduation can be eliminated by placing the object upon different portions of the scale. A large number of observations will increase the accuracy of results.

In recording observations, truthfulness is paramount. Record as an observation only that which has been observed. Several students recorded in their note-books the length of an object as observed to be 19 cms. because it extended from the 0 to the 19 division of a scale. The scale had no division at 17 and was faulty. The length of the object was 18 cms. The students

should have noted what they observed, and not what they inferred.

The record should always indicate the accuracy of an observation. If an ammeter which is readable to the hundredth of an ampère should indicate a current of exactly 2 ampères, the record should be 2.00, not simply 2. The two ciphers in the decimal places, although of no numerical value, still indicate the accuracy of the observation, and to what extent the observation may be relied upon.

Perfect freedom in the matter of drawing inferences is not compatible with a course of electrical measurements. Original research and investigation alone give this. Yet the failure of many experiments to yield reasonable results upon first trial give to the student the opportunity of inferring the causes of the failure, and it is advisable that the student should unassisted determine these causes.

The student is admonished:

1. To interfere in no other student's experiments.
2. To consider neatness and cleanliness as essential to good work.
3. To disconnect all apparatus after use.
4. To arrange and adjust all apparatus so that the greatest accuracy is obtained with the least inconvenience to the observer.

RESISTANCES.

Comparison of Resistances.—It is not often that the determination of a resistance in absolute measure is required. In nearly all cases a resistance is measured only in so far as its ratio to some known standard resistance is determined. Standard resistances are made of German silver, platinoid, or manganin wire, and are wound bifilar. These substances are chosen because of their high resistivity, and because of their small variation in resistance with the temperature. If the resistance of a conductor at 18° C. be R, then its resistance at any near temperature, t, may be represented by the formula

$$R_t = R\,[1 + (t - 18)a],$$

where a is the temperature coefficient.

For German silver $a = 0.00024$ to 0.0006.
For copper $a = 0.004$.
For carbon $a = -0.0002$ to -0.0007.
For electrolytes $a = -0.014$ to -0.030.

Attention is called to the fact that the resistance of metals increases with a rise in temperature, while the resistance of carbon and electrolytes decreases.

Rheostats or resistance-boxes are stamped with a *normal temperature.* This means that, at the given temperature, the resistance of all the coils in series is exactly equal to their nominal value. The individual coils, however, may none of them have the exact resistance with which it is stamped. A table of corrections should accompany each box. By applying the correction and then correcting for temperature, the exact resistance of any coil may be obtained.

E.g.: The correction for a 100-ohm German silver coil is + 0.12 at the normal temperature 18.8°, and the temperature coefficient is 0.00035. At 21.8° the resistance

$$= 100.12[1 + (21.8 - 18.8)0.00035] = 100.23 \text{ ohms.}$$

Care must be taken that the resistance of a connecting wire be not, through oversight, added to a resistance to be compared or to a standard. If it must of necessity be added, its value should be added or its influence considered. Bad contacts often add resistance in unsuspected places. The ends of connecting wires should be scraped and fastened firmly in the binding posts. The plugs of a rheostat should be twisted in their respective holes.

Method of Substitution.—Two resistances are equal to each other if, when one replaces the other in a given circuit, the current strength remains unaltered.

Apparatus.—Daniell cell, galvanometer, rheostat, and x.

Directions.—Form a circuit of cell, galvanometer, and x. Note deflection θ. Substitute for x such a resistance R_1 as to yield a deflection θ_1 slightly less than θ. Then substitute R_2 so as to yield θ_2 slightly larger than θ. Then

$$x = R_2 + (R_1 - R_2)\frac{\theta_2 - \theta}{\theta_2 - \theta_1}.$$

Prove formula. Why is a Daniell cell used?

What accuracy have you attained?

This method is used in determining insulation resistances, which are very large.

For measuring small resistances the galvanometer resistance should be small. Why?

Direct Method (Ohm). — I. *Apparatus.* — Mirror galvanometer (shunted), Daniell cell, rheostat, and x.

Directions.—Form a circuit of cell, connecting wires, and galvanometer. Observe small deflection θ, which is proportional to the current C. Insert x in circuit and observe θ_x, i.e., C_x. Sub-

stitute for x a known resistance R and observe θ_2, i.e., C_2. Then

$$x = R\frac{C - C_x}{C - C_2}\ \frac{C_2}{C_x} = R\frac{\theta - \theta_x}{\theta - \theta_2}\ \frac{\theta_2}{\theta_x}.$$

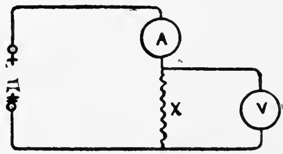
Evidently this method is good for measuring resistances while a current is traversing them. What difference would this make in the case of incandescent lamps? An ammeter may be used instead of a galvanometer and the currents be read off directly.

Prove the correctness of the formula.

II. *Apparatus.*—Voltmeter, ammeter, constant voltage, and x.

Directions.—Form a circuit as indicated in Fig. 401. Observe the ampères C in the ammeter A and the volts E in the voltmeter V. Let the resistance of the voltmeter be R. Then

FIG. 401.



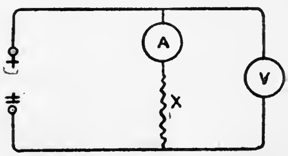
$$x = \frac{E}{C - \frac{E}{R}}.$$

Determine the probable error in your results.

III. *Apparatus.*—Same as in II.

Directions.—Form circuit as indicated in Fig. 402. Observe ampères C in A and the volts E in V. Let R = resistance of ammeter. Then

FIG. 402.



$$x = \frac{E}{C} - R.$$

Projection of Potentials. — *Apparatus.* — High-resistance sensitive galvanometer, a known resistance R, constant source of E. M. F., and x.

Directions.—Form a circuit of E. M. F. R, and x. From the extremities of x lead off to galvanometer. Note the deflection θ. Transfer the galvanometer connections to the extremities of R. Note the deflection θ_1 [R should be so chosen in respect to x that θ and θ_1 shall be nearly equal]. Then

$$x = \frac{\theta}{\theta_1} R.$$

This method is most often employed for comparing small resistances. Before making this measurement draw a diagram of the connections.

Resistivity.—The resistivity of a substance is the resistance which a cube of the substance, with faces of a sq. cm. would offer

to a current entering one face and flowing out of the opposite face. Hence the resistance of a wire, made of a substance of resistivity ρ, whose length is l cms. and whose diameter is d cms. is

$$R = \rho \frac{4l}{\pi d^2},$$

$$\therefore \quad \rho = \frac{\pi d^2 R}{4l}.$$

The resistance may be measured by the projection of potentials, l by means of a cm. scale, and d by means of a micrometer screw.

TABLE OF RESISTIVITIES.

Substance.	Resistivity at 0° C.		
Silver (annealed)	1.504	$\times$	10^{-6}
Copper (soft)	1.594	"	"
Aluminum	2.912	"	"
Platinum	9.057	"	"
Iron	9.716	"	"
German silver	20.93	"	"
Mercury	94.32	"	"
Zinc	5.626	"	"

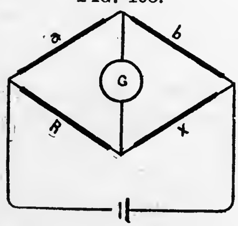
A Weston 0–150 voltmeter combined with a source of constant E. M. F.—*e. g.*, an incandescent street circuit of about 100 volts, furnishes a convenient and quick method of measuring resistances of from 5,000 to 100,000 ohms.

Directions.—Form a circuit of the voltmeter and x in series, connected with the street service. Take a reading of the voltmeter θ. Suddenly short-circuit x and observe the new deflection θ^1. Then, if R be the resistance of the voltmeter,

$$x = \frac{R\,(\theta^1 - \theta)}{\theta}.$$

Prove the correctness of the formula. Measure resistances of widely varying magnitude (lead-pencil marks on ground glass), and plot a curve with x as abscissæ and error % in results as ordinates.

FIG. 403.

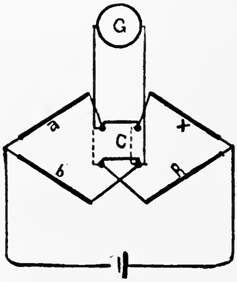


Method of Wheatstone's Bridge.—When a circuit is arranged as in Fig. 403, there will be no current in the galvanometer G, if the resistances a, b, R, and x are so proportioned that $a : b = R : x$.

Apparatus.—Resistances a and b, rheostat R, galvanometer, source of E. M. F., commutator, and x.

Directions $[a = b]$.—Connect apparatus as in Fig. 404. The commutator c serves to quickly exchange b for a in Fig. 403, and hence, if a be not exactly equal to b, two values of R (R_1 and R_2) will be found which produce an equilibrium in the bridge. The true value of x will then be

FIG. 404.



$$x = \frac{R_1 + R_2}{2}.$$

Interpolation.—In practice it is seldom that a rheostat has sufficiently small units to render it possible to effect an exact adjustment of the bridge. The value of x may be determined, however, by interpolation. Suppose that a resistance R in the rheostat nearly produces equilibrium. When the commutator is in its two positions 1 and 2, suppose the needle's readings to be m_1 and m_2 divisions respectively. *Increase* R by a small amount δ, and observe the corresponding readings n_1 and n_2. Then

$$x = R + \frac{m_1 - m_2}{(m_1 - m_2) - (n_1 - n_2)} \delta.$$

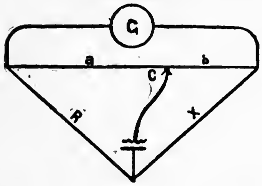
For measuring very large resistances, b should be made larger than a (10, 100, or 1,000 times). R must then be multiplied by the ratio $\frac{b}{a}$ to get x. If x be small, a is made larger than b. In these cases the commutator must be dispensed with, as well as the increased accuracy which it affords.

Wire Bridge.—In the bridge formula $x = \frac{b}{a} R$ it is immaterial whether the absolute values of b and a be known or not, as long as the ratio $\frac{b}{a}$ be known. If b and a be together the resistances offered by two portions of a stretched uniform wire, and contact be made between a and b with the galvanometer by means of a sliding knife edge, the ratio $\frac{b}{a}$ will be equal to the ratio of the two lengths of the wire comprised between the contact and the two ends of the wire respectively. For the resistances offered by two wires of the same material and cross section are proportional to the lengths of the wires.

Apparatus.—Stretched wire with sliding contact, galvanometer, standard resistance R, source of E. M. F., and x.

Directions.—Connect as in Fig. 405. Slide the contact c along the wire $a\,b$ until the galvanometer shows no deflection. Measure the lengths of a and b. (The whole wire is usually made 1,000 units long, hence, if a be measured, $b = 1{,}000 - a$.) Then

FIG. 405.



$$x = \frac{b}{a} R.$$

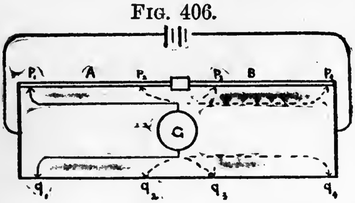
By comparing Figs. 403 and 405 it will be noticed that the battery and galvanometer have been exchanged. Why?

Method of Mathiesen and Hockin.—To compare the conductivities of two substances.

Apparatus.—Two wires of the same cross-section made of the two substances, sensitive galvanometer, stretched wire with sliding contact, and source of E. M. F.

Directions.—Send a current through the stretched wire in multiple arc with the two wires which are to be compared, and which are arranged in series with each other. Connect one terminal of the galvanometer to a point p_1 of one of the wires. Connect the other terminal with a point q_1 on the stretched wire, so that no current flows through the galvanometer. Proceed similarly with p_2q_2, p_3q_3, and p_4q_4. Then

FIG. 406.



$$\frac{\text{Resistance } p_1p_2}{\text{Resistance } p_3p_4} = \frac{\text{Length } q_1q_2}{\text{Length } q_3q_4}.$$

If $p_1p_2 = p_3p_4$, then

$$\frac{\text{Conductivity } A}{\text{Conductivity } B} = \frac{\text{Length } q_3q_4}{\text{Length } q_1q_2}.$$

Why?

BATTERY RESISTANCES.

Method of Ohm.—*Apparatus.*—Galvanometer of low resistance G, rheostat, cell of internal resistance x.

Directions.—Form a circuit of cell, rheostat, and galvanometer in series. Adjust R in rheostat so as to give a proper deflection θ. Add a resistance R' in the rheostat so that the deflection θ' is

about half θ. Then, if the deflections be proportional to the currents,

$$x = R' \frac{\theta'}{\theta - \theta'} - (R + G).$$

This formula results from

$$(1) \qquad \theta = \frac{E}{G + x + R},$$

$$(2) \qquad \theta' = \frac{E}{G + R + R' + x}.$$

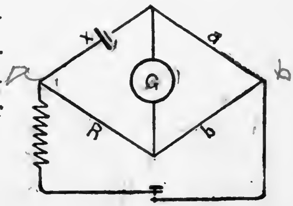
A Weston ammeter may be employed in place of the galvanometer, and it yields quick results.

Method of Mance.—*Apparatus.*—Galvanometer, wire bridge or two known resistances, rheostat, key, cell of internal resistance x.

Directions.—Connect the cell in one arm of the Wheatstone's bridge, and in the customary position of the battery place a key and suitable resistance. Manipulate a, b, or R so that the galvanometer *gives the same deflection* whether the key be closed or not. Then

$$x = \frac{a}{b} R.$$

FIG. 407.



The magnitude of the galvanometer deflection may be regulated by a copper wire shunted between its terminals.

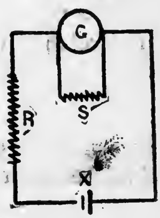
This method is unreliable in its results. The E. M. F. of a cell is somewhat dependent on the current. If the key circuit is of small resistance, the E. M. F. will be changed by the closing of the key.

Method of Thomson.—*Apparatus.*—Galvanometer, rheostat, shunt for galvanometer, cell of internal resistance x.

Directions.—Connect the cell, plugged rheostat, and shunted galvanometer in series. Adjust shunt for a suitable deflection. Remove shunt of resistance S and bring in circuit a resistance R from rheostat, so as to produce the same deflection as before. If G be the galvanometer resistance, then

$$x = \frac{RS}{G}.$$

FIG. 408.



The current C in the galvanometer is the same in each observation. In the first case

$$C = \frac{S}{G+S} \cdot \frac{E}{x + \frac{GS}{G+S}}.$$

In the second case

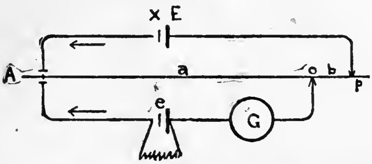
$$C = \frac{E}{x + R + G},$$

whence

$$\frac{S}{Gx + Sx + \frac{G^2S}{G+S} + \frac{GS^2}{G+S}} = \frac{1}{x+R+G} \therefore x = \frac{RS}{G}.$$

Method of Beetz.—*Apparatus.*—Stretched wire of known resistance per unit length provided with two sliding contacts, galvanometer, shunted cell, double key, cell of internal resistance x.

FIG. 409.



Directions.—Connect circuit as indicated in Fig. 409, both cells tending to send a current toward A. At A is a key connecting both cell circuits with the stretched wire Ap. Leaving p in place, shift o until no deflection occurs in the galvanometer G, upon suddenly closing the key at A. Shift p to a new position, p', and find a corresponding point, o', which shall produce an equilibrium. Representing the resistances of Ao, op, Ao', and $o'p'$ by a, b, a', b', respectively, we have

$$x = \frac{ab' - a'b}{a' - a},$$

minus the resistance of the conducting wires.

Proof.—Inasmuch as no current flows in G, the current C in the stretched wire is the same as in the branch AEp. Hence

$$E = C\,(x + a + b),$$

if we neglect connecting wires. Also the difference of potential V between A and o is

$$V = Ca.$$

In the second adjustment we have

$$E = C'(x + a' + b')$$

$$V = C'a'$$

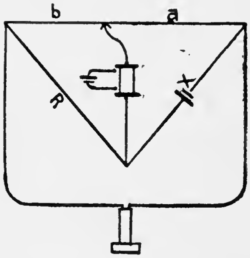
$$\frac{E}{V} = \frac{x + a + b}{a} = \frac{x + a' + b'}{a'}$$

$$\therefore x = \frac{ab' - a'b}{a' - a}.$$

This method gives the resistance of the cell E on open circuit. It may also be used to determine the resistance of a cell which has been previously short-circuited through a resistance. This resistance can be thrown out at the moment of contact at A.

Method of Kohlrausch.—*Apparatus.*—Induction coil (of low resistance secondary), cell to operate it, telephone receiver, wire bridge, cell of internal resistance x.

FIG. 410.



Directions.—Connect the cell in one of the arms of the Wheatstone's bridge. Connect the secondary of the induction coil with the sliding contact and the junction between R and x. Substitute a telephone for the galvanometer of an ordinary bridge combination. Adjust a and b so that a minimum loudness is heard in the telephone. Then

$$x = \frac{a}{b} R.$$

Why can a telephone be used and not a galvanometer?

Resistivity of Electrolytes.—If a vessel containing an electrolyte and supplied with platinized platinum electrodes be substituted for the cell in Fig. 410, the resistance of the electrolyte may be determined in the same manner as the internal resistance of the cell. Owing to the high temperature coefficient of electrolytes the vessel should be placed in a water bath in order to maintain the temperature constant. The temperature of the electrolyte may be obtained from a thermometer with its bulb submerged in the electrolyte, if the vessel is of suitable shape. If the contrary be the case, the temperatures of the bath and electrolyte may be assumed alike. The resistance R of the electrolyte is dependent on the size and shape of the vessel and on the position of the electrodes. To obtain the resistivity it is necessary to substitute for

the electrolyte another of known resistivity ρ' and obtain its resistance R'. Then the resistivity of the original electrolyte

$$\rho = \frac{R}{R'}\rho'.$$

As a standard solution saturated NaCl (specific gravity = 1.201) may be used. Its resistivity at 18° is 4.657 ohms. This decreases 0.104 ohm for each degree rise of temperature.

COMPARISON OF E. M. F.'S.

The Clark standard cell has an E. M. F. at the temperature t of

$$1.434\,[1 - 0.00115(t - 15)] \text{ volts.}$$

It should never be short-circuited or closed through less than 10,000 ohms. For comparing the E. M. F. x of a cell with that of the standard E_s, by means of a tangent* galvanometer, we have the following methods:

Method of Unequal Resistances and Deflections.—*Apparatus.* — Galvanometer, resistance-box, standard cell, and cell x.

Directions.—Form a circuit of the standard cell and the rheostat with resistance R_s, through the galvanometer whose reduction factor is K. Observe the deflection θ_s. Substitute x for the standard and with a resistance R_x note θ_x. Then, if B_s and B_x be the resistances of the standard and x and G of galvanometer, we have

$$(1)\qquad K \tan.\, \theta_s = \frac{E_s}{B_s + R_s + G},$$

and

$$(2)\qquad K \tan.\, \theta_x = \frac{x}{B_x + R_x + G},$$

whence

$$(3)\qquad x = \frac{(B_x + R_x + G)\tan.\,\theta_x}{(B_s + R_s + G)\tan.\,\theta_s}E_s.$$

Consider whether you may neglect B_s and B_x.

Method of Equal Resistances.—If you arrange so that $B_x + R_x + G = B_s + R_s + G$, then (3) reduces to

$$(4)\qquad x = \frac{\tan.\,\theta_x}{\tan.\,\theta_s}E_s.$$

* Small deflections obtained with a telescope and straight scale are proportional to the tangents of the angular deflections of the needle.

Method of Equal Deflections.—If R_s and R_x be so adjusted that $\theta_x = \theta_s$, then

$$x = \frac{B_x + R_x + G}{B_s + R_s + G} E_s. \tag{5}$$

Method of Sum and Difference. — *Directions.*—Connect both standard and x in series and with the total resistance of the circuit R of such a [large] magnitude as to obtain a suitable deflection θ. Reverse one of the cells so that both tend to send currents in opposite directions. Note the deflection θ'. Then

$$\frac{E_s + x}{E_s - x} = \frac{\tan.\ \theta}{\tan.\ \theta'}.$$

$$\therefore \quad x = \frac{\tan.\ \theta - \tan.\ \theta'}{\tan.\ \theta + \tan.\ \theta'} E_s.$$

Method of Wheatstone.—*Directions.*—Form a circuit with standard cell, suitable resistance, and galvanometer. Note deflection θ. Add R_s to the circuit and note deflection θ'. Substitute x for the standard and adjust resistance so as to obtain θ. Add R_x to get θ'. Then

$$x = \frac{R_x}{R_s} E_s.$$

Derive the formula.

Polarization.—*Apparatus.*—Two platinum electrodes in a beaker of dilute H_2SO_4, Daniell cell, dead-beat low resistance (shunted) galvanometer, key, watch with seconds hand, and rheostat.

Directions.—Form a circuit of key, cell, 1,000 ohms, beaker, and galvanometer in series. Close key and note deflections every thirty seconds for ten minutes. Take a reading at the instant of closing, if possible. Remove the platinums and heat to a red glow in a Bunsen burner. Replace and change the 1,000 ohms to 100 ohms. Repeat the operation of reading. Reduce the resistance to 10 and then to 0 ohms. Take readings every fifteen seconds in the last two cases. Plot the four resulting curves with deflections for ordinates and time for abscissæ. What inferences can be drawn from the results? What causes polarization? How is it obviated in the Daniell, Bunsen, and Le Clanche cells? Why heat the platinum?

MEASUREMENT OF CURRENTS.

Reduction Factor of a Galvanometer.—The reduction factor K of a galvanometer is such a constant that the current C which passes through the galvanometer is expressed as a function of the angular deflection ω of the needle by the equation

$$C = K \tan. \omega.$$

Apparatus.—Telescope-reading galvanometer, standard Daniell cell, rheostat, and meter rod.

Directions.—Measure the voltage E of the cell and the resistance G of the galvanometer. Then form a circuit of cell, galvanometer, and resistance-box. Vary the resistances R in the rheostat, noting the corresponding deflections θ. Measure the distance d of the middle point of the scale from the galvanometer mirror. [In the same units as those of the scale, *e.g.*, millimetres.] Calculate the currents from E, G, and R's. Calculate the ω's from the formula

$$\tan. 2\,\omega = \frac{\theta}{d}.$$

Calculate the reduction factors K for the different currents and make a table. Plot a curve with tan. ω for ordinates and C for abscissæ.

The currents may be read directly by inserting a Weston ammeter, if the galvanometer be suited for moderately strong currents.

Reduction Factor of an Electro-dynamometer.—If a current C, flowing through an electro-dynamometer, needs a torsion angle θ to bring the needle back to zero, the reduction factor K connects C and θ by the formula

$$C = K\sqrt{\theta}.$$

Why?

Apparatus.—Electro-dynamometer, ammeter, lamp-board resistance, street circuit.

Directions.—Form a circuit of all the apparatus in series, and varying the lamps in circuit, note C's by the ammeter and corresponding θ's of the electro-dynamometer. Calculate K in each case and form a table. Plot a curve with θ's for ordinates and C's for abscissæ.

Electro-chemical Equivalents of Copper and Hydrogen.—One coulomb [1 ampère for 1 second] theoretically disengages 0.1157 cu. cm. of hydrogen [at 760 mm. and 0°] at the cathode of an electrolytic vessel containing dilute H_2SO_4, and 0.000328 gram of copper from a solution of $CuSO_4$.

Apparatus.—Hoffman H_2SO_4 voltameter with cock at the bottom, copper voltameter, Weston ammeter, lamp-board, street circuit, clock, thermometer, barometer.

Directions.—Fill the voltameter with a dilute solution of chemically pure H_2SO_4. Form a fresh deposit on the cathode of the copper voltameter. Wash the cathode, dry it under an air-pump, and weigh. Let the weight be w grams.

Form a circuit of ammeter, two lamps in multiple arc, voltameter in series. Close the circuit and note the time t. Allow the current to flow until one tube of the voltameter is nearly filled with hydrogen. Turn off current, noting time t'. Let the acid run out of the lower cock of the voltameter until the level in the reservoir tube is the same as in the hydrogen tube. Read off the cu. cms. q of hydrogen. Note barometer height h. Take the temperature $t°$ of hydrogen by placing the thermometer alongside the tube. Read the ammeter every thirty seconds that the circuit is closed. Let the average current be C. Wash, dry, and weigh [$= w'$ grams] the copper cathode. $C\,(t' - t)$ coulombs, in passing through the circuit, have deposited $(w' - w)$ grams of copper and

$$\frac{q}{1 + 0.00367\,t°}\;\frac{h}{760}\text{ cu. cms. of hydrogen.}$$

Verify the theoretical equivalents, *i.e.*, amount per coulomb in each case.

Heat Effects.—C ampères flowing through R ohms for t seconds liberate C^2Rtx gram calories of heat. You are required to determine x.

Apparatus.—Calorimeter, distilled H_2O, thermometer, bare German silver coil, balance, ammeter, lamp-board resistance, and clock.

Directions.—Measure the resistance R of the coil. Submerge the coil in q grams of H_2O placed in the calorimeter. Place the thermometer so that the bulb is in the centre of the coil. Connect the lamp-board, ammeter, and coil in series. Close the circuit and note the time t_1 and temperature $t_1°$. When the temperature [the H_2O being continually stirred] reaches about 30° [$=t_2°$], open the circuit, noting time t_2. Read the ammeter and ther-

mometer every thirty seconds that the circuit is closed. If the average current be C and the water value of the calorimeter be w,

$$x = \frac{(t_2^\circ - t_1^\circ)\ (w + q)}{C^2 R\ (t_2 - t_1)}.$$

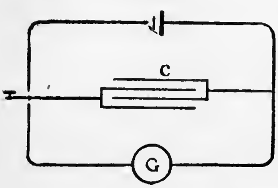
It is well to have the original temperature of the water as much below the temperature of the room as it will be above that temperature at the close of the experiment. Plot a curve of temperature and time. Explain its form.

CONDENSERS.

If a condenser of C farads capacity be charged with Q coulombs, the two terminals will have a difference of potential of V volts determined by the condition $Q = C\,V$. If a condenser charged successively with Q_1, Q_2 . . . units be discharged through the same galvanometer yielding the [small] amplitudes of the first vibrations θ_1, θ_2 . . . then $Q_1 : Q_2 : \ldots = \theta_1 : \theta_2 : \ldots$ The deflections θ are termed "throws" or "kicks."

To Compare Capacities.—*Apparatus.*—Double key, standard condenser C, condenser of capacity x, ballistic galvanometer, and Daniell cell.

FIG. 411.



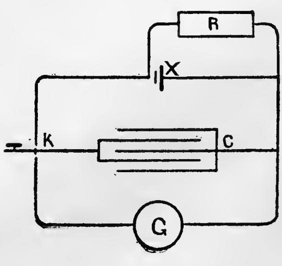
Directions.—Connect up the standard as in Fig. 411. Close the key and observe the throw θ. Substitute the condenser of unknown capacity for the standard. Observe the throw θ'. Then

$$x = \frac{\theta'}{\theta}\ C.$$

The ratio of the E. M. F. of two cells may be easily determined by means of the condenser. They are to each other directly as the throws which they cause in the galvanometer when connected successively with the same condenser as in Fig. 411.

To Determine the Internal Resistance of a Cell by Means of a Condenser.—*Apparatus.*—Condenser, C, ballistic galvanometer, G, double contact key, K, rheostat, R, and cell of internal resistance x.

FIG. 412.



Directions.—Form circuit as in Fig. 412, leaving out an infinity plug in the rheostat. Press the key and release it. Observe the throw θ in the galvanom-

eter. Replace the infinity plug leaving a resistance R in the rheostat. Again close and release the key observing the throw θ'. Then

$$x = R\frac{\theta - \theta'}{\theta'}.$$

Prove that the formula is correct.

MAGNETISM.

Moment of Inertia.—The moment of inertia K of a cylinder magnet l cms. long and of r cms. radius and weighing m grams, referred to an axis perpendicular to the axis of the cylinder at its middle point is

$$K = m\left(\frac{l^2}{12} + \frac{r^2}{4}\right);$$

measure l by a scale, $2r$ by micrometer screw, and m by a balance. Calculate K.

Time of Oscillation of a Cylindrical Magnet.—*Apparatus.*—Cylinder magnet, suspension case, seconds striking clock.

Directions.—Suspend magnet so that, when no torsion is exerted by the suspension, the magnet sets north and south. Affix a light paper pointer to magnet over a mark in the case. Set the magnet in vibration by approaching another magnet. Starting at any convenient time, mentally count the seconds as they are struck by the clock and, in your note-book, record the exact times of 50 successive passages of the pointer over the mark in the case. (Instead of a pointer, a mirror may be attached to the magnet and the passage of the zero point of a scale can be observed in a telescope.) The seconds must be divided into 10 parts by estimate. A little practice enables one to do this well.

Of the 50 observed times, cast away the first 5 and the last 5. Divide the remaining 40 into 4 groups of 10 successive times. In each group take the arithmetical mean of the 1st and 10th, 2d and 9th, 3d and 8th, 4th and 7th, 5th and 6th. Take the mean of the means of each group. You have then four absolute points in time. The magnet made 20 oscillations between the 1st and 3d points and 20 between the 2d and 4th points. The time of a single oscillation $\tau = \frac{3^d - 1^{st}}{20} = \frac{4^{th} - 2^d}{20}$. From K and τ calculate $MH = \frac{\pi^2 K}{\tau^2}$ | M = magnetic moment of the cylinder, H = earth's horizontal intensity.

Determination of $\frac{\mathbf{M}}{\mathbf{H}}$.—*Apparatus.*—Magnetometer, cylin-

der magnet, rack to hold magnet in same horizontal plane as the needle of the magnetometer, meter rod.

Directions.—Place rack so as to hold magnet in an east-west direction with its middle point in the same horizontal plane as the magnetometer needle and directly north of it. Place magnet at a distance r cms. from the needle and read the deflection θ of the magnetometer needle. Reverse the magnet end for end and read the deflection θ'. Average these readings. Repeat the operation with the magnet at a shorter distance r' cms. from the needle, obtaining an average deflection ϕ (r should be equal to about 1.4 r'). Then

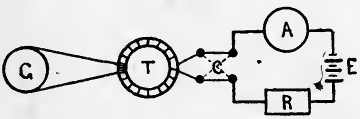
$$\frac{M}{H} = \frac{r^5 \tan. \theta - r'^5 \tan. \phi}{r^2 - r'^2}.$$

From the values of $\frac{M}{H}$ and MH determine M and H. Calculate the *specific magnetism* $= \frac{M}{\text{wt. in grams}}$.

Magnetization Curve of Iron or Steel.—*Apparatus.*—Test ring *, T, wound with a primary and secondary coil, ammeter, A, adjustable resistance, R, commutator, C, ballistic galvanometer, G, and source of current, E.

Directions.—Connect the apparatus as in Fig. 413. Adjust R so as to yield the maximum current to be employed. With the galvanometer circuit broken, commutate a few times to get the iron into a cyclic condition. Close the galvanometer circuit, and, commutating once, observe the throw of the galvanometer, θ, at the same time read the ampères, c, by the ammeter. Repeat this operation with various currents. The magnetizing forces are proportional to the current strengths, and the induction in the iron is proportional to the throws of the galvanometer. If the current in the primary of N turns be c ampères

FIG. 413.



* The dimensions of the test ring and the number of turns of wire in the primary and secondary are dependent on the sensibility of the galvanometer and the availability of current for the primary magnetizing coil. The following ring is suitable for a test with the cheap D'Arsonval galvanometers mentioned before. The ring is annular, of rectangular cross-section, with an internal diameter of 5 inches, an external diameter of 6 inches, and a depth of 2 inches. If the primary be wound with one layer of No. 16 wire (250 turns), 5 ampères will be the maximum current required. The secondary needs but 4 or 5 turns.

and the arithmetical mean of the internal and external diameters be d cms., the magnetizing force

$$H = \frac{4\pi}{10\pi}\frac{Nc}{d} \text{ gilberts.}$$

If the throw θ in the galvanometer connected with n turns around the ring, whose cross-section is A square cms., results from a reversal of the main current, c, then the flux density corresponding to this H is

$$B = \frac{100\ r}{2\ An} k\theta \text{ gausses,}$$

where r is the resistance of the galvanometer plus the secondary coil, and k is the galvanometer coefficient, *i.e.*, the micro-coulombs of electricity which are necessary to cause a throw of 1 scale division in the galvanometer. To obtain the value of k it is necessary to charge a microfarad condenser with a cell of E volts, discharge it through the galvanometer, and immediately afterward connect the terminals of the galvanometer by a resistance equal to the resistance of the secondary coil on the ring. This latter is necessary because the damping of a galvanometer is dependent on the external resistance. The charge, discharge, and short circuit can be conveniently accomplished with the assistance of a two-tongued top-and-bottom contact key. Plot a curve with B for ordinates and H for abscissæ.

Test Nail.—This exercise is to determine the distribution of force along a bar magnet. If a piece of soft iron be placed in the field of a magnet, a pole, proportional to the field's strength, will be induced. The force exerted will be proportional to the strength of field × strength of pole, *i.e.*, proportional to the square of the field strength.

Apparatus.—Bar magnet, piece of wood of the same size as the magnet, soft iron armature, suspended from a spring whose elongation may be measured on a graduated circular scale, meter rod.

Directions.—Determine the 0 of the scale with the armature resting upon the piece of wood. Substitute for the wood the magnet and, using the 0 just found, determine the extension of the spring necessary to detach the armature from various points of the magnet. Representing the distances of these points from the middle of the magnet by D, and the extension by F, form a table of D, F, $\sqrt{F}$ and $\sqrt{\frac{F}{D}}$. Plot a curve of F and D.

CALIBRATIONS.

Rheostat.—*Apparatus.*—Wire bridge, galvanometer, rheostat, 1-ohm coil, and standard 100-ohm coil.

Directions.—Determine the correction for the 500 division of the bridge wire by balancing two 10-ohm coils against each other and then, exchanging them, balancing them again. The mean of the two bridge readings gives the electrical centre or 500 of the wire. (500 − mean) is the correction which must be applied in all the subsequent readings. Now, assuming the auxiliary 1 ohm as correct, determine the assumed correct value of the 1 ohm in the rheostat. Compare these two 1 ohms with the 2-ohm coil, and find its assumed correction. Similarly compare 3 with corrected 1 + 2; 4 with 3 + 1; 10 with 4 + 3 + 2 + 1; 20 with 10 + 4 + 3 + 2 + 1; etc. You thus obtain a table of assumed corrections, which would be correct at the correct temperature for the assumed standard 1-ohm coil. Now compare the 100 in the rheostat with the standard 100 coil. From the actual correction for the 100, thus obtained, subtract the assumed correction. Add $\frac{1}{10}$ of this difference to the assumed correction for the 10; $\frac{1}{100}$ to the assumed correction for the 1; $\frac{4}{10}$ for the 40; etc. Make a table of corrections.

Bridge Wire.—From the known values of the resistances the electrical position of any portion of the bridge wire can be obtained. The bridge reading minus the electrical position = correction. Find the correction for every 50th division.

Ammeter.—*Apparatus.*—Standard ammeter, adjustable resistance, current to the maximum capacity of the ammeter to be calibrated.

Directions.—Arrange all the apparatus in series. Adjust the resistances so as to produce a current $\frac{1}{10}$ of the maximum range of the ammeter to be calibrated. Read both the ammeters at the same time. Repeat this operation with different currents throughout the range of the instrument. Plot a curve with the readings of the standard for abscissæ and those of the other ammeter for ordinates.

Voltmeter.—*Apparatus.*—Standard voltmeter, two adjustable resistances, E. M. F. to the maximum capacity of the voltmeter to be calibrated.

Directions.—Connect the two resistances in series with the E. M. F. Connect both voltmeters in multiple arc with the terminals of one of the resistances. By manipulating the resistances impress various voltages on the voltmeters, making simultaneous readings from the two instruments at each of the voltages. Plot a curve as in the case of the ammeters.